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Controlling Pollution from the Manufacturing and Coating of Metal Products. 1. Metal Coating Air Pollution Control

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Prepared for

Foster D. Snell, Inc., Cleveland, OH

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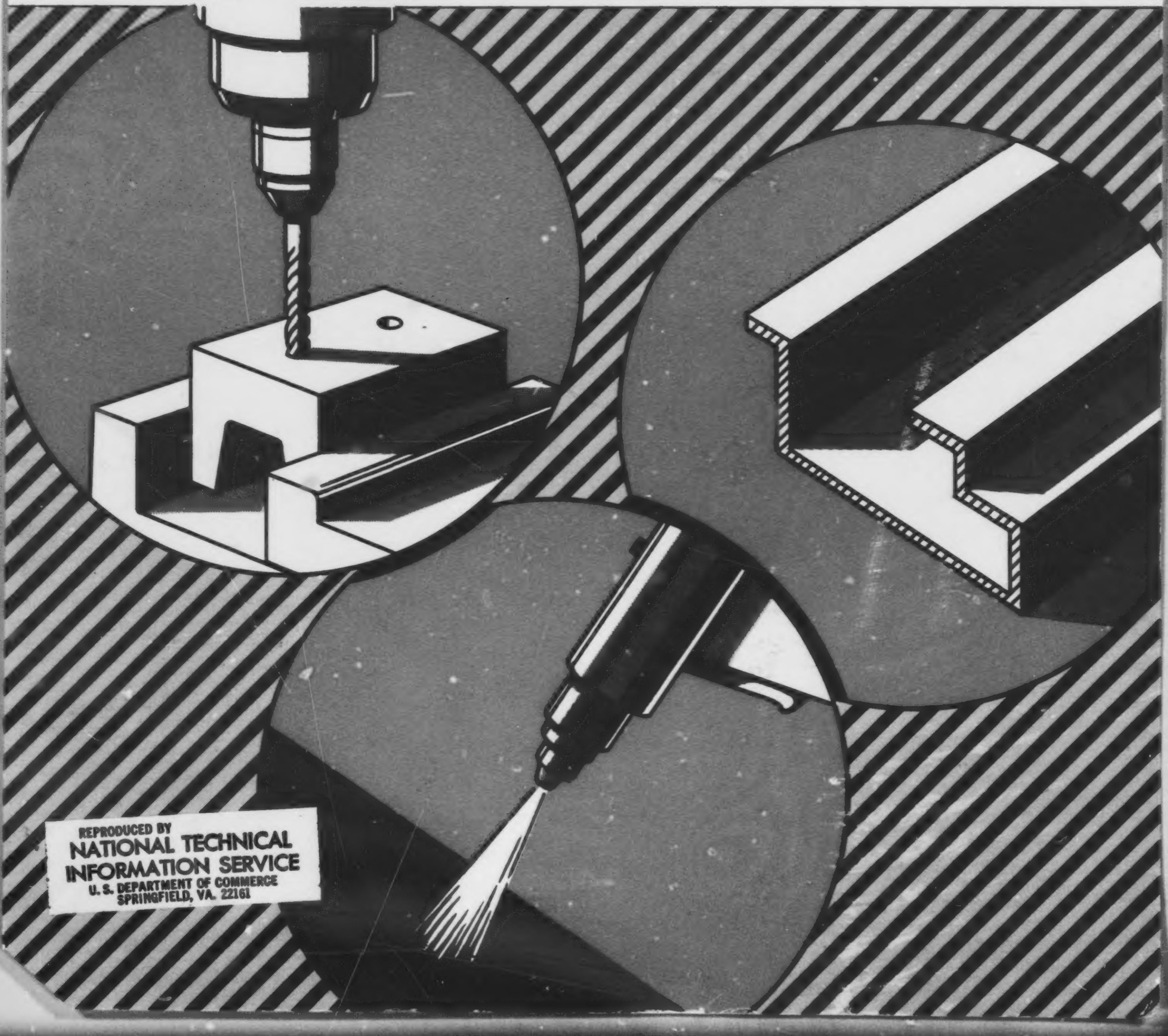
Controlling Pollution from the Manufacturing and Coating of Metal Products

Metal Coating Air Pollution Control

PB 299672

EPA Technology Transfer Seminar Publication



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The first volume acquaints supervisory and management personnel in the industry with methods of reducing the emission of organic solvents to the atmosphere and helps them assess the costs. Volume 2 outlines for plant operators practical and proven techniques for controlling hydrocarbon emissions from metal cleaning operations, along with appropriate cost data. Volume 3 addresses managers, engineers and other industry personnel responsible for resolving the water pollution problems of a manufacturing facility. It covers regulations, in-plant controls, three methods for wastewater treatment, establishment of a working relationship with a municipality and a case history.

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METAL COATING
AIR POLLUTION CONTROL – I

U.S. ENVIRONMENTAL PROTECTION AGENCY
Environmental Research Information Center • Technology Transfer

MAY 1977

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The technical information in this publication was prepared by Burton J. Sutker of Foster D. Snell, Inc., and Uday Potankar of JACA Corporation.

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INTRODUCTION

Recent findings of high levels of hydrocarbons in the nation's air have spurred renewed activity by the U.S. Environmental Protection Agency (EPA) toward their control. One result will be more emphasis on reducing hydrocarbon emissions from industrial activity. EPA's Office of Air Quality Planning and Standards will shortly publish guidelines to the states for control of these emissions in several industries, including metal coating. In the next 2 years, federal standards for new plant construction in these industries are also expected.

In the metal painting and coating industry, most hydrocarbon emissions are traceable to the solvent in the coating material, all of which eventually evaporates. Our purpose is to acquaint supervisory and management personnel in the industry with methods of reducing the emission of organic solvents to the atmosphere and to help them assess the costs. We will be as practical as possible and will present a number of realistic options.

The logical sequence of steps toward achieving compliance suggests a division of this publication into two parts.

Part A is concerned with reducing and controlling hydrocarbon emissions at their in-plant sources. It includes background material on the nature of hydrocarbon emissions and step-by-step information on plant surveys and emission control procedures.

Part B details the techniques available for end-of-line treatment of these emissions. Because these techniques often involve the use of heat energy, methods for recovery of this heat will also be described.

This handbook is part of the U.S. Environmental Protection Agency Technology Transfer Seminar Series for the Machinery and Mechanical Products Industry. A companion publication discusses control of air pollution from metal cleaning processes, and a third volume delineates water pollution control in the metal industry.

This publication, like the others in the series, provides practical, realistic options, based on the current literature and on the experience and know-how of people throughout the industry.

Part A

REDUCING HYDROCARBON EMISSIONS THROUGH IN-PLANT PROCESS CHANGE

Part B

TREATMENT OF HYDROCARBON EMISSIONS AND HEAT RECOVERY

May 1977

U.S. Environmental Protection Agency
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Part A

REDUCING HYDROCARBON EMISSIONS THROUGH IN-PLANT PROCESS CHANGE

CHAPTER I

PHYSIOCHEMICAL FACTORS AFFECTING HYDROCARBON EMISSIONS IN COATING OPERATIONS

The following topics are basic to the understanding and discussion of hydrocarbon emissions and their control. They include:

- Definition of Organic Solvents
- Evaporation Rates
- Atmospheric Concentrations
- TLV and LEL
- Reactive Hydrocarbons
- Calculations for Determining Reactivity of a Coating Formula

DEFINITION OF ORGANIC SOLVENTS

Volatile organic substances have been defined in the Federal Register (CFR 52.1596, subsections (a) (i) and (k)) as follows:

> "Organic materials mean chemical compounds of carbon excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides, metallic carbonates and ammonium carbonates and having a vapor pressure of 0.02 pounds per square inch absolute or greater at standard conditions, including but not limited to petroleum fractions, petrochemicals and solvents.
>
> For the purposes of this section, organic solvents include diluents and thinners which are liquids at standard conditions and which are used as dissolvers, viscosity reducers, or cleaning agents."*

Although this definition was evolved for a specific region,** it is EPA's most recent designation of the hydrocarbons to be controlled in maintaining acceptable atmospheric burdens.

**Federal Register*, Volume 38 - No. 218, November 13, 1973, pp. 31398-31399.

**For "New Jersey portions of the New Jersey, New York, Connecticut Interstate and Metropolitan Philadelphia Interstate Air Quality Control Regions."

EVAPORATION RATES

The vapor pressure of a chemical compound, central to its evaporation rate, relates only to its temperature. It has been measured for most of the pure compounds; tables of value are readily available for most normal plant circumstances.*

There are several empirical relationships between volatility (or relative evaporation rate) and vapor pressure. According to Gaynes, "The simplest form for calculating relative evaporation rates is multiplying the molecular weights in question by the vapor pressures."**

For example, ethyl acetate has about the same vapor pressure as ethyl alcohol, yet it evaporates twice as fast because its molecular weight is twice that of the alcohol. This comparison is also true for butyl alcohol and butyl acetate or ethyl alcohol and toluol.

Tysall and Wheeler state that "the rate at which a solvent evaporates from a film is a technological measurement—combining the effect of a number of basic physical properties such as vapor pressure, latent heat of evaporation and density of solvent vapor.†

Doolittle presents typical evaporation rates for a series of solvent compounds by comparing them to n-butyl acetate, which is arbitrarily given a rate value of 1.†† Figure 1 shows that the rates range from 1 to 3,000.

Finally, evaporation rate is influenced by air circulation over the surface of the solvent coating; the higher the volume of air, the faster the evaporation.

ATMOSPHERIC CONCENTRATIONS

In discussing air pollution, we are naturally concerned with concentration levels of pollutants. There are three main methods for calculating concentrations of solvent vapors: partial pressure, volume, and milligrams per cubic meter.

PARTIAL PRESSURE

There is a general relationship between the amount of a solvent in the air and the vapor pressure of this solvent. At any temperature a solvent will continue to evaporate until the air becomes saturated, much as water evaporates to cause humidity. At a normal atmospheric pressure of 760 mm of mercury, the mixture of air and solvent vapor will behave as if each exerted a pressure the total of which would be 760 mm. The solvent will exert its own vapor pressure, called partial pressure.

---

*For instance, see *Chemical Engineers' Handbook.* Perry et al., New York: McGraw-Hill.

**Gaynes, N. I., *Metal Finishing*, Volume 74, No. 1, Jan., 1976, p. 29.

†Tysall and Wheeler, *The Science of Surface Coating.* New York: Van Nostrand, 1962.

††Doolittle, The Technology of Solvent and Plasticizers, 1954.

	Relative Evaporation Rate with n-Butyl Acetate at 1.0
Methyl chloride	27.5
Isopropyl alcohol	3.0
n-Butyl acetate	1.0
Xylene	0.63
Dipentene	0.08
di-Ethylene glycol monethyl ether	0.01

Source: *The Technology of Solvent and Plasticizers*. Doolittle, 1954.

Figure 1. Typical Evaporation Rates

In a fixed volume of air, enough solvent will evaporate to create that pressure. For instance, at temperature T, if a solvent has a vapor pressure of 200 mm of mercury there will be in that mixture of air and solvent vapor enough solvent to represent $\frac{200}{760}$ of the total volume. This also means that in a mole of the mixture there will be $\frac{200}{760}$ mole of the solvent and $\frac{560}{760}$ mole of air. If the solvent has a molecular weight of 92 and the air a molecular weight of 29, there will be 24.2 lbs. $\left(\frac{200}{760} \times 92\right)$ of solvent and 21.4 lbs. $\left(\frac{560}{760} \times 29\right)$ of air, for a total weight of 45.6 or a weight concentration of 53 percent solvent and 47 percent air. This is useful for calculating emissions measured in pounds of solvent per hour.

VOLUME

Another way of expressing the concentration of solvent vapor is by volume, stated either in percent by volume or in parts per million (ppm). In the case mentioned above, the concentration of the solvent vapors in percent by volume would be $\left(\frac{200}{760} \times 100\right)$, which is 26.3 percent. Expressed in ppm, the concentration would be 263,000 ppm.

MILLIGRAMS PER CUBIC METER

Finally, there is a way, increasingly used, to express concentrations in milligrams per cubic meter (mg per m^3). Using the above example, the concentration would be 24.2 gm (26.3% x 92) of solvent in 22.4 liters, which converts to 24,200 mg $\times \frac{1000}{22.4} = 1.08 \times 10^6$ mg/m^3.

The solvent used in all these calculations is highly volatile. In the case of a less volatile solvent, xylene, the figures at 20°C would be approximately:

- Concentration by weight = 2.3%.
- Concentration by volume = 0.66% or 6,600 ppm.
- Concentration by $mg/m^3 = 693 \times \frac{1000}{22.4} = 31{,}000\ mg/m^3$.

These calculations assume conditions under which solvents can evaporate into fixed volumes of static air and give the maximum concentrations under circumstances of ideal equilibrium. In most industrial operations, air is moving so that equilibrium is not achieved and actual concentrations are lower.

TLV AND LEL

There are two values of the air concentrations of a given solvent vapor that are of considerable importance to industry: the threshold limit value (TLV) and lower explosive limit (LEL).

- TLV relates to toxicity expressed in ppm and is an arbitrary value based on physiological considerations. It represents the conditions under which it is believed that nearly all workers may be repeatedly exposed, day after day, without adverse effects.*
- LEL, the lower explosive limit, represents a property of the vapor. It is the lowest solvent concentration at which the mixture does not sustain combustion. For insurance and for other obvious reasons, it is industry practice to provide enough ventilation to maintain a solvent concentration well below this limit. The usual value is set at 25 percent of the LEL. Explosive limits are usually given in percent by volume; one percent is equal to 10,000 ppm.

TLV, LEL, and 25-percent LEL values for some typical classes of solvents are given in Figure 2. You will note that TLV's are much lower than even the 25-percent LEL. The practical importance of this fact will be discussed later.

In the above discussion of concentrations, the equilibrium concentration of xylene by volume was shown to be 6,600 ppm at 20°C. As shown in Figure 2, the TLV is 100 ppm and the LEL is 10,000 ppm. This means that about 60 times more air than is necessary for evaporation has to be supplied to comply with the TLV and about 2.5 times more to comply with the 25-percent LEL.

In general, TLV and LEL requirements demand much larger volumes of exhaust air than are necessary from a strictly operational point of view.

---

*N. Irving Sax, *Dangerous Properties of Industrial Materials.* Fourth Ed., New York: Van Nostrand Reinhold Company, 1975.

	TLV	LEL	25% LEL
Toluene	200	13,000	3,300
Xylene	100	10,000	2,500
Isopropyl alcohol	400	25,000	6,300
Methyl-ethyl-ketone	200	18,100	4,500
n-Butyl acetate	150	17,000	4,300
Methylene chloride	500	None	None

Source: N. Irving Sax, *Dangerous Properties of Industrial Materials.* Fourth Ed., New York: Von Nostrand Reinhold Company, 1975.

Figure 2. Comparison of TLV and LEL for Some Solvents (ppm/volume)

REACTIVE HYDROCARBONS

Because of the national scope of coating operations, it is expected that a federal policy will be proposed through the Environmental Protection Agency. Major consumers of hydrocarbon-based coatings, such as the automotive, coil, and can coating segments of the metal coating industry, will be a prime initial target for emission guidelines. This could lead to guidelines for other high-volume repetitive coating operations such as those for paper, textiles, wood, and adhesive laminations. To date, there are no federal guidelines for hydrocarbon emissions from coating operations.

Meanwhile, many states and other political subdivisions have either proposed or actually enacted legislation to limit atmospheric contamination by hydrocarbon emissions. For instance, California, particularly the Los Angeles basin area, has promulgated Rules 66, 102, and 442, to be discussed shortly.

Industry personnel should become familiar with the terminology in existing regulations so they can determine whether the solvents they use are likely to be affected by later guidelines.

Solvents used in coating processes are classified according to their photochemical reactivity. Briefly, photochemical reactivity, sometimes shortened to "reactivity," is "the tendency of an atmospheric system containing the organic compound in question and nitrogen oxides to undergo, under the influence of ultraviolet radiation (sunlight) and appropriate meteorological conditions, a series of chemical reactions that result in the various manifestations associated with photochemical air pollution. These include eye irritation, vegetation damage and visibility reduction."*

**Control Techniques for Hydrocarbon and Organic Solvent Emissions from Stationary Sources*, AP.68, EPA.

As a result of these definitions and because of severe local smog conditions, a special regulation was issued to cover use in the Los Angeles area of materials containing reactive hydrocarbons. This is "Rule 66," which has become a byword for legislation on hydrocarbon emissions. In part, it reads:

> "For the purposes of this rule, a photochemically reactive solvent is any solvent with an aggregate of more than 20 percent of its total volume composed of the chemical compounds classified below or which exceeds any of the following individual percentage composition limitations, referred to the total volume of solvent:
>
> (1) A combination of hydrocarbons, alcohols, aldehydes, esters, ethers, or ketones having an olefinic or cyclo-olefinic type of unsaturation: 5 percent;
>
> (2) A combination of aromatic compounds with eight or more carbon atoms to the molecule except ethyl-benzene: 8 percent;
>
> (3) A combination of ethyl-benzene, ketones having branched hydrocarbon structures, trichloroethylene, or toluene: 20 percent."

There has been considerable controversy, however, about the facts on which Rule 66 was based and especially about its applicability to areas other than the Los Angeles basin.

The rule was eventually amended by two other rules of the Southern California Air Pollution Control District:

1. Rule 102 changed the listing of solvents in Rule 66 by the following additions or subtractions:

Type (1) Solvents — perchloroethylene is excluded.

Type (2) Solvents — methyl benzoate and phenyl acetate are excluded.

Type (3) Solvents — no change.

To aid industry in determining if specific coating formulas were in compliance, an expanded tabulation was issued by the Air Resources Board (ARB) in Resolution 76-12 of February 19, 1976. It states:

> "Now, Therefore, Be It Resolved, the Air Resources Board hereby adopts for the purposes of inventory and planning, the classification of organic compounds according to photochemical reactivity as set forth in Appendix V attached hereto."

The Appendix V referred to in the resolution is presented here as Figure 3.

2. Rule 442, the second rule amending Rule 66, imposed specific limitations on emissions. Note that these are not clear as to definition of a coating line or entire coating plant, although subsection (b) uses the word "collectively."

Class I (Low Reactivity)	Class II (Moderate Reactivity)	Class III (High Reactivity)
C_1-C_2 Paraffins	Mono-tert-alkyl-benzenes	All other aromatic hydrocarbons
Acetylene	Cyclic Ketones	(including partially halogenated)
Benzene	Alkyl acetates	Aliphatic aldehydes
Benzaldehyde	2-Nitropropane	Branched alkyl Ketones
Acetone	C_3+ Paraffins	Cellosolve acetate
Methanol	Cycloparaffins	Unsaturated Ketones
Tert-alkyl alcohols	n-alkyl Ketones	Primary & secondary C_2+ alcohols
Phenyl acetate	N-methyl pyrrolidone	Diacetone alcohol
Methyl benzoate	N,N-dimethyl acetamide	Ethers
Ethyl Amines	Alkyl Phenols (1)	Cellosolves
Dimethyl formamide	Methyl phthalates (2)	Glycols (1)
Perhalogenated Hydrocarbons		C_2+ Alkyl phthalates (2)
Partially halogenated paraffins		Other Esters (2)
Phthalic Anhydride (2)		Alcohol Amines (2)
Phthalic Acids (2)		C_3+ Organic acids + di acid (2)
Acetonitrile (1)		C_3+ di acid anhydrides (2)
Acetic Acid		Formin (2) (Hexa methylene-tetramine)
Aromatic Amines		Terpenic hydrocarbons
Hydroxyl Amines		Olefin oxides (2)
Naphthalene (1)		
Chlorobenzenes (1)		
Nitrobenzenes (1)		
Phenol (1)		

(1) Reactivity data are either non-existent or inconclusive, but conclusive date from similar compounds are available; therefore, rating is uncertain but reasonable.

(2) Reactivity data are uncertain.

Source: Communication from the State of California Air Resources Board, Appendix V, Resolution 76-12.

Figure 3. ARB Reactivity Classification of Organic Compounds

"(a) A person shall not discharge organic materials into the atmosphere from equipment in which organic solvents or materials containing organic solvents are used, unless such emissions have been reduced by at least 85% or to the following:

(1) Organic materials that come into contact with flame or are baked, heat cured or heat polymerized, are limited to 1.4 kilograms (3.1 pounds) per hour not to exceed 6.5 kilograms (14.3 pounds) per day.

(2) Organic materials emitted into the atmosphere from the use of photochemically reactive solvents are limited to 3.6 kilograms (7.9 pounds) per hour, not to exceed 18 kilograms (39.6 pounds) per day, except as provided in subsection (a) (1). All organic materials emitted for a drying period of 12 hours following their application shall be included in this limit.

(3) Organic materials emitted into the atmosphere from the use of non-photochemically reactive solvents are limited to 180 kilograms (396 pounds) per hour not to exceed 1350 kilograms (2970 pounds) per day, except as provided in subsection (a) (1). All organic materials emitted for a drying period of 12 hours following their application shall be included in this limit.

(b) Equipment designed for processing a continuous web, strip or wire which emit organic materials shall be collectively subject to the limitations stated in subsection (a).

(c) Emissions of organic materials into the atmosphere required to be controlled by subsection (a) shall be reduced by:

(1) Incineration, provided that 90 percent or more of the carbon in the organic material being incinerated is oxidized to non-organic materials, or

(2) Incineration, provided that the concentration of organic material following incineration is less than 50ppm, calculated as carbon and with no dilution, or

(3) Adsorption, or

(4) Processing in a manner determined by the Air Pollution Control Officer to be not less effective than (1) or (3) above."*

---

*Communications from State of California Air Resources Board, July 26, 1976.

CALCULATIONS FOR DETERMINING REACTIVITY OF A COATING FORMULA

Each coating formula containing solvents may have to be revised according to Rule 66 or Rule 102. For determining if revision is necessary to achieve conformity, use the calculations that follow.

For evaluating solvents in connection with Rule 66:

Given: A coating solvent with the following composition:

Toluene	15.0%
Xylene	2.0%
Methyl isobutyl ketone	7.0%
Isophorone	10.0%
Saturated aliphatic solvents	66.0%
Total	100.0% by volume

Problem: To determine if this solvent system is photochemically reactive as defined by Rule 66.

Solution: Tabulate the materials in the solvent that may be photochemically reactive. Columns (1), (2), and (3) refer to the photochemically reactive groupings listed on page 8.*

Chemical Name	Classification Name	(1)	(2)	(3)
Toluene	Aromatic hydrocarbon	0 %	0 %	15.0%
Xylene	Aromatic hydrocarbon	0	2.0	0
Methyl isobutyl ketone	Branched alkyl ketone	0	0	7.0
Isophorone	Cyclic ketone	10.0	0	0
Aliphatic solvents	C_3 + paraffins	0	0	0
Total		10.0%	2.0%	22.0%
Limit		5.0%	8.0%	20.0%

---

*Readers may need a chemical handbook to relate these compounds–and those used in their plants–to the classifications in Columns (1), (2), and (3) of Rules 66 and 102.

This system is photochemically reactive on three counts:

- The group (1) total exceeds the 5 percent allowance.
- The group (3) total exceeds the 20 percent allowance.
- The total of all groups (34 percent) exceeds the 20 percent total allowance.

Utilizing the expanded ARB tables and definition of Rule 102, the positioning of various solvents changes as follows:

Chemical Name	(1)	(2)	(3)
Toluene			15.0%
Xylene			2.0%
Methyl isobutyl ketone			7.0%
Isophorone		10.0%	
Aliphatic solvents		66.0%	
Total	0.0%	76.0%	24.0%

The significant differences between Rule 66 and Rule 102 (plus the ARB tables) are the movement of some solvents into higher reactivity categories and the inclusion of aliphatic solvents as part of the reactivity calculation.

CHAPTER II

PLANT OPERATING FACTORS AFFECTING HYDROCARBON EMISSIONS

The first part of this chapter will be a discussion of emissions from various coating formulas and thicknesses.

In the second part, we will examine the steps of the coating process to see what each contributes to the total emission picture.

NON-PROCESSING FACTORS AFFECTING EMISSIONS

The amount of organic emission is related to:

- Composition of the coating;
- Amount of coating applied;
- Post-application chemical changes; and
- Non-solvent contaminants.

COMPOSITION OF THE COATING

As we have seen, the amount of solvent emitted depends on the composition of the coating material.

Figure 4 shows in very general terms the amounts of solvent emitted under the same conditions from various coating compounds. In general, low-solids lacquers will produce more emissions than high-solids urethanes, and significantly more than waterborne systems.

Some typical values of solvent emissions in grams per square meter for different coating systems are given in Figure 5. The five enamels shown in the figure, which contain from 29 to 57 percent solvent, will emit 52 to 79 grams per square meter. Note that there will also be some emissions from unreacted resin components and decomposition products that volatilize during baking.*

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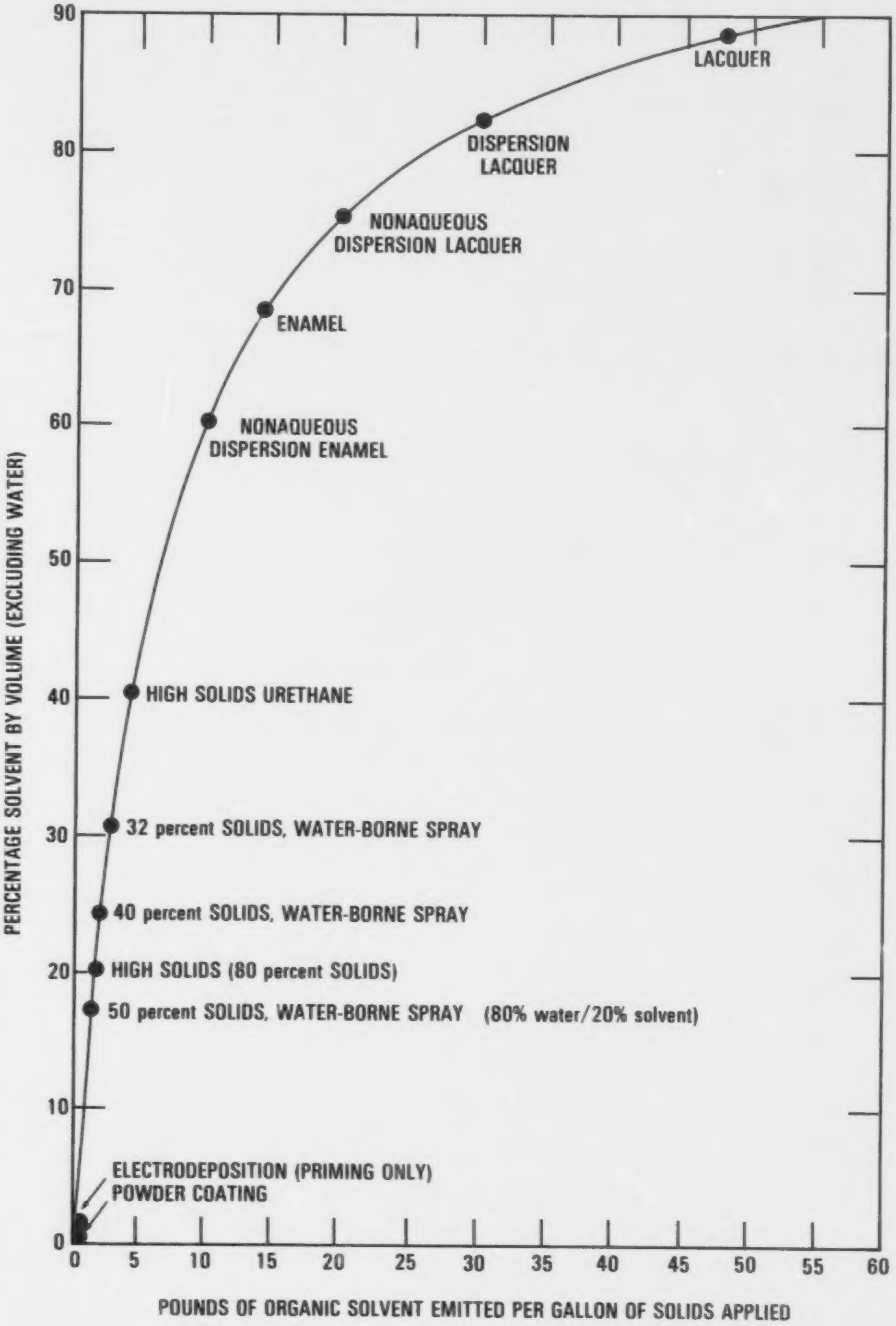
*Resin emissions generally come from thermosetting coatings that require polymerization or crosslinking of low molecular weight fractions. These components gradually build in molecular weight (with decreased volatility) as the exposure time and temperature increase. Hence, the emissions contain both solvent and polymer fractions.



Source: Private Communications.

Figure 4. Solvent Emissions from Various Coating Formulas

		Enamel, Air Dry	Enamel, Baking	Enamel, Dipping	Acrylic Enamel	Alkyd Enamel	Primer Vinyl Zinc Chromate	Primer Surfacer	Primer Zinc Chromate	Primer Zinc Vinyl Chromate	Epoxy Polymide	Vinyl	Vinyl Acrylic	Polyurethane
	Solvent:	.5703	.4323	.2912	.5242	.4683	.3872	.2150	.4343	.5473	.4029	.5811	.7588	.5071
Solvent Emissions							Emission Factor g/m^2*							
Aliphatic hydrocarbons	Mineral spirits	66.2	56.0	28.4		56.6	11.0	16.7	59.3	13.8				
Aromatic hydrocarbons	Toluene	4.4	7.5	3.4	5.5	2.1	5.3	5.6	5.0	6.0	14.4	16.7		14.8
Saturated alcohols	n-Propyl alcohol		.4	13.4			11.8	1.0	8.4		17.5		77.9	
Ketones	Methyl ethyl ketone				60.2		9.0			42.2	22.9	66.7	13.9	9.7
Saturated esters	n-Butyl acetate			1.7	10.2		9.9	10.3			14.0			50.8
Saturated esters	Ethylene glycol mono methyl ether						12.4	3.1		12.9				
Resin Emissions														
Alkyd	Phthalic anhydride	3.8	4.6	5.0		4.0	1.6							
Vinyl	Vinyl chloride				1.5				1.8	1.4		1.5		
Acrylic	Methyl methacrylate				1.4								1.2	
Epoxy	Epichlorohydrin							15.5						
Urethane	Toluene diisocyanate													4.6
Cellulosic	Methyl ethyl ketone													
Amino	Ethanolamine										5.0			
Resin ester	Maleic anhydride													
Styrene	Styrene													
Phenolic	Phenol													
Hydrocarbon	Turpentine													
	Total:	74.4	68.5	51.9	78.8	62.7	61.0	52.2	74.5	76.3	73.8	84.9	93.0	79.9

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*At typical coating thicknesses.

Source: Private Communications.

Figure 5. Solvent and Resin Emissions from Typical Coating Formulas

Emissions from thermoplastic coatings are almost totally solvent. These polymers are applied at high molecular weight, so that little change occurs between application and baking.

Emissions can also be linked to the nature of the part to be finished. Expected levels of emissions per-unit-produced are given in Figure 6 for some segments of the metal coating industry. Although total emissions vary significantly from a beverage can to a washer, due to the area covered, the net emissions per square meter are about the same.

Obviously, two factors must be considered in selecting coating formulas: the type of material to be coated and the characteristics of the desired finish. In a later section, we will discuss how recent developments in formulation have increased the choice of formulas, with particular significance for overall emission reduction.

In addition, an economic choice sometimes has to be made in meeting emission standards: whether to invest in emission control equipment or switch to a more expensive coating. This will be discussed later.

AMOUNT OF COATING APPLIED

The total emissions during a coating process are affected by:

- The area to be coated;
- The thickness of the coat;
- The efficiency with which it is applied; and
- The percent of solvent in the coating.

Area and thickness can be controlled to some extent by design of the part and the application technique.

Application efficiency—for instance, avoiding overspray, overcoating, and excess widths and using a minimum of passes to achieve the thickness desired—can profoundly influence total emissions and is directly controllable by operating personnel.

Figure 7 gives a simple equation for predicting the total amount of solvent emission from any operation involving non-waterborne coating.

POST-APPLICATION CHEMICAL CHANGES

Evaporation rates of individual solvents in the coating can vary to such an extent that if significant air drying occurs before baking—generally the case—the solvent mixture remaining in the coating at the beginning of the baking operation is much richer in the high-boiling solvents. For example, a solvent mixture initially consisting of equal parts of isopropyl alcohol and xylene will tend to lose isopropyl alcohol faster than xylene. Thus, after air drying, which would remove most of the isopropyl alcohol, the solvent to be removed in baking could be mostly, if not entirely, xylene.

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Type of Hydrocarbon Product	Aliphatic Hydrocarbons	Aromatic Hydrocarbons	Saturated Alcohols	Ketones	Saturated Esters	Saturated Ethers	Alkyd	Vinyl	Acrylic	Urethane	Amino	Total Grams Per Unit	Size Unit M^2	Gram Emissions /M^2
Metal Cans, Excl. Beverage	.956	.785	.166	2.657	.269	.002	.073	.055	.077	.005	.042	5.017	.0645/can	77.8
Beverage Cans	.956	.785	.166	2.657	.269	.002	.073	.055	.077	.005	.042	5.017	.0645/can	77.8
Ductwork	3112.0	2556.0	539.7	8650.0	875.7	6.30	237.3	180.6	23.10	16.80	136.50	16334.0	231/tonne	70.7
Canopies and Awnings	1556.0	1278.0	269.8	4325.0	437.9	3.20	118.6	90.3	11.6	8.4	68.2	8166.8	105/ton	77.8
Refrigerators	529.2	111.2	79.7	120.0	109.6	80.7	5.1	3.0	2.8	--	--	1041.3	9.91/unit	105.25
Screening	1.38	1.13	.24	3.83	39	.003	.10	.08	.10	.007	.6	7.860	1/m^2	7.9
Fencing	1482.0	1217.0	257.0	4119.0	417.0	3.0	113.0	86.0	11.0	8.0	65.0	7778.0	110/tonne	70.7
Enameled Plumbing Fixtures	127.7	20.7	15.8	--	17.8	16.0	2.8	--	--	--	--	200.6	1.97/unit	101.8
Dryers	336.0	107.8	52.2	45.2	74.1	54.7	1.9	1.1	1.1	Epoxy 13.6	--	687.7	6.38/unit	107.8
Washers	250.8	80.5	38.9	33.7	55.4	40.8	1.4	.8	.8	Epoxy 10.2	--	513.3	4.76/unit	86.8
Metal Doors, Excl. Garage	63.0	51.7	10.9	175.1	17.7	.1	4.8	3.7	.5	.3	2.8	330.6	4.32/unit	76.5
Gutters	3112.0	2556.0	539.0	8650.0	375.7	6.3	237.3	180.6	23.1	16.8	136.5	16334.0	231/tonne	70.7

NOTE: In Metric Tons.

Source: Environmental Protection Agency, *Source Assessment: Prioritization of Air Pollution from Industrial Surface Coating Operations.* EPA-650/2-75-019-9, February 1975.

Figure 6. Emissions from Coated Metal Parts or Assemblies

$$W = \frac{0.0623\ A\ n\ (1-0.0.1P)}{P\ \ \ f}\ \rho$$

where:

W = weight of solvent vapors in lb.

A = area coated (sq. ft.)

n = dry mils.

P = percent solids by volume

f = efficiency factor (dimensionless)
empirically determined ($f \leq 1$)

ρ = solvent density (lb./gal.)

Source: Foster D. Snell, Inc.

Figure 7. Potential Solvent Vapor Emissions from Coating Operations

Normally, however, the temperatures used in baking ovens are not high enough to cause chemical changes in the remaining volatile solvents, except for the polymerization of certain liquid monomers or oligomers (styrene, for instance).

In direct-heated, gas-fired recirculating ovens, widely used in the industry, certain changes may occur in the solvent through contact of the vapor-laden air with the heating flame. Some of the solvent may be directly burned to carbon dioxide and water; some may remain in its original chemical state; and some may be modified or chemically changed.

These modified chemical structures will result in emissions drastically different from those expected from the initial composition of the solvent mixture; however, they are still considered hydrocarbons, subject to emission controls and guidelines. They can also contribute to the formation of tarry aerosols or condensables that constitute a new component of the exhaust. Although these latter compounds are potential pollutants, they have not been covered in any hydrocarbon emission guidelines published so far. They also present potential surface-fouling problems for incinerators, adsorbers, or heat-exchange equipment.

On the other hand, since a good proportion of the solvent vapors are probably burned to CO_2 and water in the combustion area, actual amounts of organic materials emitted to the atmosphere may be less than that calculated by the standard mass balance methods.

Because of the changes that can occur during air drying and baking, stack sampling must be done to obtain the actual emissions for design and compliance purposes.

OTHER CONTAMINANTS

Coating operations produce other contaminants besides the solvent vapors. A major source of these is the spraying operation. We will discuss overspray and ways of reducing it later. For now, the relevant point is that part of the aerosol from the spray gun may dry before it reaches either the target article and/or whatever device (baffle or water curtain) has been set up to catch the wet overspray.

This dry material, in the form of particulates, will be part of the vapor exhaust. In general, the amounts thus generated are not significant. However, if adsorption devices are used for controlling the vapor emissions, the particulates will have to be filtered out because they tend to foul the activated carbon beds.

PROCESSING FACTORS AFFECTING EMISSIONS

There are a number of commonly used coating processes. A brief survey of these will be followed by discussion of emissions associated with the various processing steps.

COMMONLY USED COATING PROCESSES

The basic processes used for coating include spraying, dip coating, flow coating, coil coating, and masking.

Spraying

Typical spraying operations are performed in a booth, with a draft fan to prevent explosive or toxic concentrations of solvent vapors. Essentially, there are three spraying techniques: air atomization, airless atomization, and electrostatic.

Air atomization uses its own air source, which may be heated, filtered and/or humidified, or treated in some other fashion. Airless spraying, on the other hand, atomizes without air by forcing the liquid material through specially designed nozzles under a pressure of 1,000-2,000psi. On release to atmospheric pressure, some of the solvents in the surface coating vaporize and join with the straight hydraulic forces at the nozzle as atomizing agents. In general, with airless spraying less solvent will be volatilized in the spray booth than with air spraying, meaning that more solids may have to be removed later during air drying or baking.

During airless atomization, total volatilization of a portion of the solvent will probably occur, and emissions from this type of booth will be similar to the solvent formula. Air atomization, which is based on partial volatilization of the solvent blend, is likely to produce emissions high in low-boilers.

Electrostatic spraying projects charged coating particles into an electrostatic field created by a potential difference of about 100,000 volts between the articles sprayed and spray grids 12 inches away. The particles of wet paint from the spray gun enter this field with the same potential as the grids and are thus repelled by them and attracted to the article being sprayed.

Dip Coating

In dip coating operations, the object is immersed for the required time in a tank of the coating. When the object is removed, excess coating drains back into the tank, either directly or via a drain ramp.

Flow Coating

Articles that cannot be dipped due to their buoyancy, such as pressure bottles, are subjected to flow coating. Material is fed through overhead nozzles in a steady stream over the article. Excess coating drains by gravity from the coated object and is recirculated. Removal of excess coating material and solvents is aided by jets of heated air.

Coil Coating

Coil coating is a technique for applying finishes to long flat strips or coils of metal, on one side or both, by means of rollers similar to those in a printing press. Three power-driven rollers are normally used. One of the rollers is partially immersed in the coating material. The coating is then transferred by direct contact to a second parallel roller. The object to be coated is run between the second and third rollers and is coated by the second roller.

Masking

Masking is a technique for applying coatings where sharp, clean edges are needed; for instance, for lettering, stripping, and two-color finishes. The areas to be left uncoated are masked with cloth, plastic sheeting, tape, or a special mask derived by photography from an artwork pattern (silk screening).

The coating may then be applied by stencil or rubber squeegee. Masking is usually removed while the coating is still wet to prevent frayed edges and to ensure sharpness.

EMISSIONS FROM THE VARIOUS PROCESSING STEPS

Emissions of solvent vapor vary not only with the coating formula but also with each individual processing step.

Spraying

Paint-spray booths generally have one side open to the rest of the plant; ventilation of the booth is necessary to ensure both operator and plant safety. Normally, spray-booth ventilation velocities of from 100 to 150 feet per minute per square foot of booth opening are adequate for manual operations.* Insurance standards require that the

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**Air Pollution Engineering Manual*, AP-40, 2nd Ed., U.S. EPA, May 1973.

average velocity over the open face of the booth be not less than about 1.5 feet per second. All fumes should be vented through a fume hood instead of into the plant.

Discharge from a paint-spray booth consists of particulate matter and organic solvent vapors. The particulate matter consists of entrained coating material that did not adhere to the object being painted or to the inside surfaces of the booth. The organic vapors are generated from the evaporation of solvents, resins, diluent, or thinner.

Generally, emission levels are increased by overspray; that is, material that misses the surface to be coated. The table below gives overspray percentages for the various spray techniques.

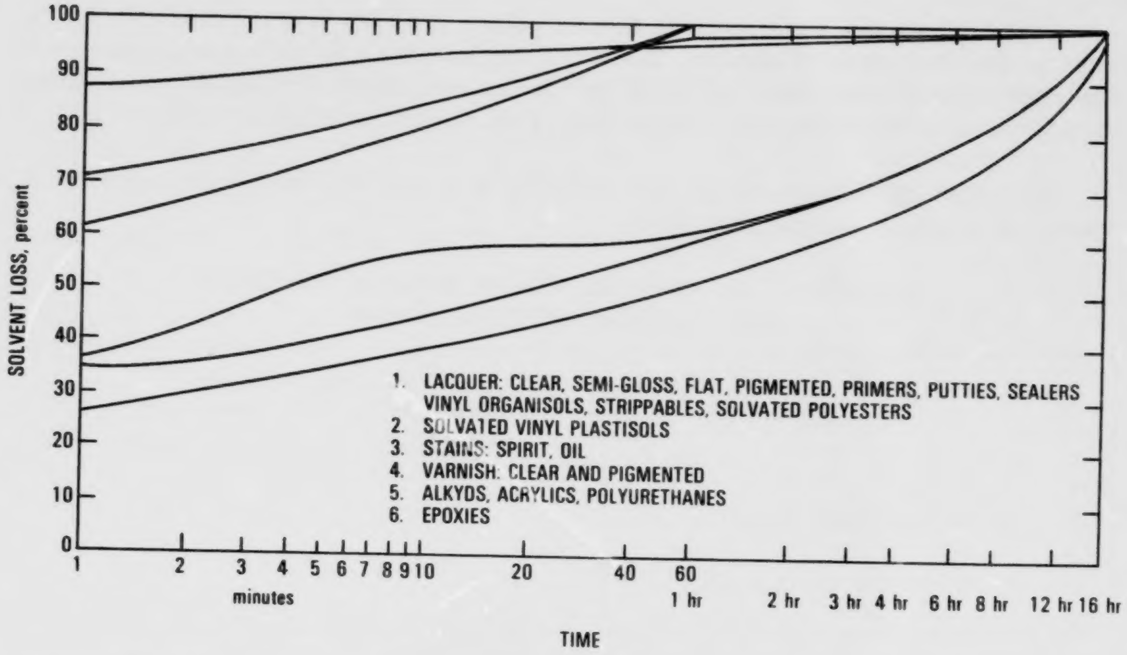
Overspray Percentages as a Function of
Spraying Methods and Surfaces Sprayed*

Method of Spraying	Flat Surfaces (%)	Table Leg Surface (%)	Bird Cage Surface (%)
Air atomization	50	85	90
Airless	20 to 25	90	90
Electrostatic			
Disc	5	5 to 10	5 to 10
Airless	20	30	30
Air atomized	25	35	35

***Air Pollution Engineering Manual,* AP-40, 2nd Ed., EPA, May 1973.

Solvent concentrations in spray booth effluents vary from 100 to 200ppm for manual operations. Solvent emissions from spray booth stacks vary with the extent of the operation, from less than 1 pound to more than 3,000 pounds per day. No definitive data is available for automatic spray booths.

Virtually all solvents evaporate in the course of the coating sequence, each at its own rate. For measuring purposes, this evaporation is viewed in terms of "flash-off," defined as the quantity of solvent evaporated under either ambient or forced conditions from the surface of a coated object during a specific time. The graph in Figure 8 shows flash-off times for various coating types applied by spraying and is useful for determining potential emissions from different coating systems. The total emission load, however, is significantly affected by the size, shape, and number of pieces being coated and other factors.



Source: *Air Pollution Engineering Manual.* AP40, 2nd Ed., EPA, 1973.

Figure 8. Evaporation Rates of Various Formulas

Solvent emissions, then, vary with types of spray operations. However, particulate matter, the other type of emission, can be effectively removed (50 - 98 percent) by techniques to control the particulate emissions. These include:

- Dry Baffle. In this method, the wet overspray collects on large panels called baffle plates, which catch 50 - 90 percent of the particulates produced by spraying a high-solids enamel. With low-solids lacquers containing highly volatile solvents, efficiencies may be much lower due to the rapid drying of the lacquer and poor adhesion of dry particles to the baffle.
- Paint Arrestor. Filter pads used in this method can remove up to 98 percent of paint particulates. Filtering velocities should be less than 1.3 m/sec.
- Water Wash. Water curtains and sprays are 95 percent effective in removing paint particulates. A water circulation rate of 1 - 5 liters per cubic meter of exhaust air is usually recommended. Surfactants may be added to the water to aid in removing paint from the circulating tank.

In order of effectiveness, the paint arrestor would be considered the best technique for removing particulates when downstream solvent vapor processes such as catalytic or other afterburners, heat exchangers, or carbon absorption beds are used. Water washing to remove particulates would be a second choice, assuming that the solvent vapor processes can tolerate some water in the vapor stream. Baffle plates would be considered the third and least effective method, although by far the cheapest.

Concentrations of water-soluble solvent vapors are sometimes reduced, particularly in non-recirculating sprays. However, this creates a water contamination problem necessitating treatment. Solvents tend to increase the BOD (biochemical oxygen demand) level of wastewater to a considerable degree (several hundred ppm).

The following table shows the effectiveness of a water curtain in reducing solvent vapors in a sample spraying operation:

Emissions from Automatic Airless Spraying Operations
(Alkyd Coating with Xylol Solvent)

Operation	Emissions in lb./hr.*	
	Particulate	Organic
Spray (no water curtain)	0.5	4.0
Spray (water curtain on)	0	3.5

*These emissions total about 60 percent of the organic emissions from this particular operation. Typically, spraying accounts for 40 - 60 percent of the total emissions from a coating operation.

Source: Foster D. Snell, Inc.

Note that in the case above the water spray reduced organic vapors discharged to the atmosphere by about 10 percent. The contaminated water was collected and the xylene recovered by separation, with the balance discarded. With highly soluble solvents, for instance methyl-ethyl-ketone, distillation may be necessary to recover the solvent and minimize sewer disposal.

Although air pollution was significantly reduced in this case, the disposal of solvent or particulate-laden water to the sewer had to be carefully monitored to keep it within water pollution guidelines. It is important, of course, to avoid substituting one set of pollution problems for another.

Flash-off occurring after the spray operation but before baking is treated later in this book as a separate category of emissions; Rule 66, however, includes pre-baking emissions as part of spraying.

Other Application Techniques

Emissions from other application techniques such as flow coating, dip coating, or coil coating differ from spray coating emissions to the extent that these methods require less coating material. However, the expected solvent emission load from these techniques can vary widely.

In fact, flow coating may not be much better from an emission standpoint than spray coating. For flow coating, the proper percentage of solids and correct viscosity must be maintained. Further, so much solvent is lost during recirculation and air blow-off of excess coating that flow coating is often done in a "tunnel" to keep the solvent-laden air in a fixed area. The result is that a well-run flow coating operation using 60,000 gallons of coating per year may use as much as 54,000 gallons of makeup solvent to compensate for "tunnel solvent" losses. This is much more wasteful than an air-atomized spray operation with 50 percent overspray.

Dip coating solvent losses are generally under 10 percent, depending on time of year and temperature in the plant. This usually represents much less solvent loss than that occurring with spraying or flow coating and does not normally require much makeup solvent.

From the standpoint of overall emissions, the single most efficient coating method is roller or coil coating, a process in which extraneous evaporation is practically negligible, since all coating supplied to the coating head is placed onto the web to be coated.

Pre-Drying Processes

Enough solvent must evaporate before the coated part enters the finishing or curing oven to avoid bubbling, uneven coating thickness, and other adverse effects. Along with solvent evaporation, the pre-drying process allows time for the coating to level itself if it has been unevenly applied. The skilled coating formulator can often vary solvent balances to minimize these problems, as well as to reduce emissions from the pre-drying operation.

Pre-drying is usually carried out on conveyors, which are often open to the atmosphere. As will be discussed later, it may be advantageous to enclose these conveyors to maintain the highest permissible vapor concentration in the air surrounding the drying parts. This allows a gentler drying of the coating to help prevent blisters or bubbles in the curing oven. Care must be taken, however, to ensure that the atmosphere in the oven is in keeping with LEL determinations.

Emissions from pre-dryers will, in general, contain higher concentrations of the low-boiling components of the solvent blend.

Ovens

The last step in coating operations is the final conditioning of the coating. While certain coatings can be totally air dried, this is usually too slow for industrial processes. In general, heat must be applied to speed the curing rate.

A distinction can be made between drying and baking. Drying generally refers to removal of volatiles such as solvents. Baking is the process by which a coating cures or otherwise changes to develop its film integrity. However, this distinction has less effect on emissions than the methods used and the type of oven.

There are two basic types of ovens: continuous and batch.

From an emission standpoint, the difference is important only insofar as the atmosphere of a batch oven is easier to control than that of a continuous oven. However, solvent evolution in a batch oven is a function of time and temperature, meaning the coated part generally reaches the temperature required for baking the finish, making subsequent handling difficult.

In a continuous oven, the evolution of solvent vapors varies in different zones of the oven. This may enable more control, depending on the configuration of the oven's exhaust system. In general, emissions in continuous ovens are more diluted than those in batch ovens, reducing problems with LELs. However, this dilution can make emission control in exhaust gases from continuous ovens more difficult and expensive.

Ovens also differ in the way they provide heat. Oven design should allow for:

- Sufficient time before contact with heat for the coated surface to level and for highly volatile solvents to evaporate slowly, inhibiting bubble formation;
- An initial low-temperature zone for continued slow evaporation of solvents, to further inhibit bubbles;
- Sufficient time and temperature for a full cure of the coating;
- Termination of the heating process before the coating is damaged;
- A cool-down zone to set the coating and enable handling;
- Removal of emissions to prevent their interference with the curing process; and
- Enough air flow to keep the atmosphere at approximately 25 percent of LEL, well below the explosive limit, to be maintained by control of coating formulation, air flow rate, and other variables.

Along with the basic design of a curing oven, a choice of heat source must be made. This may be dictated by both the fuel or energy available and the emissions expected. Types of oven heating include:

- Direct-fired gas heat, in which the products of combustion combine directly with the process air. Oven burners may use either fresh makeup air or recirculated oven gases containing evaporated solvents and other volatiles. Flame contact with recirculated gases may cause molecular cracking or conversion, which may render the effluent gases photochemically active.
- Indirect-fired gas heat, in which combustion products pass through one side of a heat exchanger and discharge directly into the atmosphere. Process air, heated before being circulated to the oven, passes through the other side.
- Electrical heat, in which fresh makeup air or oven gases are passed over electrical resistance or infrared heaters. This is similar to direct gas-fired heat, but it eliminates combustion products. However, some solvent modification can result from contact with the heating elements when resistance heaters are used.

In general, electrical heating costs more than direct-fired gas, but total emission loads are reduced.

Baking or curing ovens can produce a variety of pollutants in addition to pure "emissions" from the coating including (a) smoke and other products of incomplete combustion resulting from improper operation of a gas- or oil-fired combustion heating system, which can interfere with stack sampling procedures by fouling test elements; and (b) aerosols arising from the partial oxidation of organic solvents exposed to flame and/or high temperatures and from chemical reactions that occur in the resins (these can be deposited on heat exchangers, adsorption beds, and related hardware, reducing their effectiveness).

Emissions from ovens, therefore, vary significantly with the oven type (batch or continuous), method of heating, condition of the part before it enters the oven (predried), and oven-operating parameters such as the allowable LEL.

Emissions from the Overall Coating Process

In most coating operations, 40 - 80 percent of the solvent evaporates at the time of application and/or during subsequent air drying. The remaining 20 - 60 percent evaporates in the oven.

The table below provides an overview of this chapter and gives general emission ranges as a percentage of the total emission load from typical coating operations.

Percent of Total Emissions from Various Coating Steps

Coating Method	Coating Step		
	Application	Pre/Air Dry	Bake
Spray Coat	30-50	10-30	20-40
Flow Coat	30-50	20-40	10-30
Dip Coat	5-10	10-30	50-70
Roller Coat	0-5	10-20	60-80

Source: Foster D. Snell, Inc.

In a specific example, 30 percent of the emissions occurred during the spray process itself and another 8 percent occurred in the conveyor between the spray booth and the continuous curing oven.

CHAPTER III

PLANT SURVEYS OF HYDROCARBON EMISSIONS

An important early step in controlling emissions is to determine the volumes generated and their sources. Plant operators need to know which operations are most responsible for solvent pollution. Identifying emissions from each process is essential to developing a central plan for complying in a cost-effective and practical manner.

The plant survey gives this information and provides a basis for determining if the plant is in violation of regulations and to what degree. To carry out an effective plant survey the following steps are necessary:

- Obtain the latest regulatory requirements;
- Determine which coating operations are affected by the regulations;
- Determine which coating operations are major emitters;
- Estimate the emissions from the sources identified;
- Measure the level of emissions; and
- Develop a plan to minimize emissions and improve the plant's compliance position.

OBTAINING THE REGULATORY REQUIREMENTS

Most cities and states have Air Pollution or Air Control Offices. Contact the one in your area for the latest regulations that may affect the operation of your plant. District offices of the U.S. Environmental Protection Agency should also be asked for any relevant information.

There is always a tendency to let sleeping dogs lie and avoid involving local regulatory agencies if at all possible. It is better, however, to be aware of existing and potential regulations and guidelines as they are promulgated. One reason is that construction and operating permits are required for any equipment causing emissions, and states keep records of these in order to later implement air pollution control plans.

DETERMINING COATING OPERATIONS TO BE REGULATED

Since emission standards vary from one area to another, a coating line may be in compliance in one state and in violation in another. Opportunity may thus exist, over the short term, for a company to increase production in a plant bound by less stringent emission standards, allowing time for bringing all coating lines into compliance without a loss in production.

IDENTIFYING MAJOR EMITTERS

Coating operations should be assessed in terms of their overall contribution to total plant emissions. Large volumes of solvents used to clean applicator rolls contribute to solvent emissions, yet are not generally included in coating-line solvent calculations. Spray booths used intensively but for short periods of time must be considered. "Tunnel losses" from flow coating lines contribute significantly to emissions. A noncoating operation, such as panel degreasing, may be an important emitter. Finally, if a plant makes its own coating, this operation can also be a major emitter.

ESTIMATING AMOUNT AND TYPE OF EMISSIONS

Once the plant has determined the major sources of emissions, an overall tabulation should be made of the amounts and types. This tabulation must include solvents used for makeup, dilution, and cleaning.

Coating suppliers should be contacted to find out the percentage of solids and types of solvents in their products. This also serves notice to the supplier that the plant is interested in compliance-type solvents.

Ideally, each article would be coated and then weighed immediately after both air drying and baking to determine how much weight loss (emission) takes place at each step. Based on these weights, and on the temperatures of drying and baking and the formulation supplied by the coating manufacturer, an estimate could be made of the type of emissions from each stage of the process. Obviously, this would not be practical for auto bodies, refrigerator paneling, and other large items. Sample coupons or small panels might be interjected into the coating line to obtain the information for large pieces, however.

As a first approximation, the daily consumption of coating multiplied by the percent of solvent would produce a total solvent emission load. This total load would then be factored according to the breakdown in the table on page 26, presented to show percentage of emissions from individual process steps. As stack testing is expensive, some states accept the results of such material-balance calculations.

MEASURING EMISSION LEVELS

The only reliable method for determining actual emissions is to measure them in the effluent streams. The major effluent stream for gaseous emissions is the stack, which transports the final emissions after the stream has passed through paint arrestors, water wash towers, adsorption devices, catalytic afterburners, etc.

However, the validity of this method, relied on more and more by regulatory agencies, is impaired because of the following factors:

- Measurements are based on volumetric quantities, which are significantly affected by temperature;
- Many of the analytical techniques commonly used do not give a real value for the amount of material in a given volume of gas, and empirical factors have to be applied;
- Variations in air flow and/or concentrations are difficult to compensate for with current equipment; and
- Some of the emissions may be compounds for which no standard analyses are available.

Stack sampling results are also affected by the point at which the sample is taken. Although continuous operations would tend to produce a uniform level of emissions, batch operations can produce constantly changing emission loads. This means that for a total picture of a given plant's operation, continuous monitoring is probably required.

A further problem with stack sampling is that, in general, emissions from a plant or coating line are discharged through more than one stack. Therefore, each has to be monitored, unless the exhaust can be combined before sampling.

PLANNING FOR COMPLIANCE

Once it has been determined that a certain coating operation is the major emitter, steps should be taken to reduce its emission load by formula changes, process modifications, or other means.

This should be followed by effective policing to ensure that the changes are, in fact, producing the desired emission reduction. The second major emitter should then be approached in the same manner.

In any comprehensive survey and action program, the services of outside experts may be worthwhile. Experienced consultants have an up-to-date awareness of current regulatory thinking, without preconceived biases as to how the regulations should be approached or applied. They have access to the latest technology in stack sampling procedures, which can shorten the training period for plant personnel. Finally, consultants, using the plant's stack analyses and their familiarity with the regulations, can advise plant managers how compliance may best be achieved.

CHAPTER IV

EMISSION REDUCTION BY IN-PLANT PROCESS CHANGE: OPPORTUNITIES AND PROBLEMS

Earlier in this publication, the various approaches to emission reduction were broadly presented. In this chapter, we will discuss technical and economic aspects of formula changes and the potential impact of process changes.

EMISSION CONTROL THROUGH FORMULA CHANGES

The problem associated with formula changes can be both technical and economic. Before discussing these problems, we assume that experimentation has been or will be performed to ensure that the new coating meets predetermined specifications, that adequate supplies of the coating are available, and that plant personnel are fully trained in its application. Finally, the revised coating must be checked at the outset against internal cost standards, a point illustrated by the sharply varying costs of the polymer systems in Figure 9. The data, although 8 years old, also illustrates the wide variety of coating systems available. Note that silicone and fluorochemical polymers are still the most expensive.

The main ways of varying formulas are discussed below, in terms of both advantages and problems.

SOLVENT CHANGES

As a result of regulations affecting the use of photochemically reactive solvents, practically all the conventional formulas are now available with "conforming" solvents. This means that the new formulations meet the requirements and limitations of old Rule 66, discussed earlier.

Figure 10 shows some of the types of systems that meet the requirements and the compositions of their solvents.

The solvent-changing approach, however, has two main limitations: (a) emissions of non-photochemically reactive solvents are still limited by Rule 442, discussed earlier, to 396 pounds per hour and a maximum of 2,970 pounds per day; and (b) reformulations generally result in higher costs. For example, a 100-percent xylene thinner costs about 60 cents per gallon. The cost of the complying substitute formula in Figure 10 would be 90 cents per gallon.

Dominant resin-type in coating	Rel cost/ft^2 of a 2-mil thickness of coating
Oxidizing alkyd	1.00
Oxidizing alkyd and melamine and/or urea	1.30
non-Oxidizing alkyd and melamine	1.50
non-Oxidizing alkyd and urea	1.35
Vinyl chloride-acetate copolymer	1.50
Acrylic-type copolymers	4.00
Styrenated alkyds (oxidizing)	1.10
Phenolic	1.70
Epoxy	2.00
Epoxy and melamine	1.50
Melamine and ethylcellulose	1.50
Polyurethane and alkyd	1.60
Silicone	10.00
Silicone and alkyd	7.00
Allyl ester copolymers	6.00
Polyamide (nylon) 10 mils. flame spray	5.00
Polytetrafluoroethylene (Teflon) flame spray	13.00
Poly (chlorofluoroethylene) (Kel-F)	11.00

Source: Kirk Othmer, *Encyclopedia of Chemical Technology*, 2nd Ed., Volume 5. Interscience. 1968.

Figure 9. Relative Costs of Coatings

Type of surface coating	Weight, lb/gal	Composition of surface coatings, % vol						
			Hydrocarbon					
		Nonvolatile portion	Aliphatic saturated	Aromatic	Alcohols saturated	Ketones	Esters saturated	Ethers saturated
Enamel, air dry	7.6	39.6	93.5	6.5				
Enamel, baking	9.1	42.8	82.1	11.7	6.2			
Enamel, dipping	9.9	59.0	58.2	7.2	30.9		3.7	
Acrylic enamel	8.9	30.3		6.9		80.6	12.5	
Alkyd enamel	8.0	47.2	92.5	7.5				
Primer surfacer	9.4	49.0	18.0	8.9	21.8	16.5	16.8	18.0
Primer, epoxy	10.5	57.2	44.8	15.9	3.0		28.8	7.5
Primer, zinc chromate	10.3	37.8	80.0	7.2	12.8			
Primer, vinyl zinc chromate	8.4	34.0	17.5	7.9		60.0		14.6
Epoxy-polyamide	10.5	34.7		19.9	26.4	34.5	19.2	
Varnish, baking	6.6	35.3				97.0		3.0
Lacquer, spraying	7.9	26.1	7.0	1.7	21.3	23.2	45.1	1.7
Lacquer, hot spray	8.4	16.5	16.4	6.8	24.3	17.2	14.8	20.5
Lacquer, acrylic	8.4	38.2	10.0	18.5	3.5	42.0	26.0	
Vinyl, roller coat	7.7	12				43.5		56.5
Vinyl	8.9	22.00		18.9		81.1		
Vinyl acrylic	7.5	15.2				84.9	15.1	
Polyurethane	9.2	31.7		19.7		13.9	66.4	
Stain	7.3	21.6	80.6	14.0		0.1		5.3
Glaze	7.8	40.9	91.6	8.4				
Wash coat	7.1	12.4	40.6	14.7	10.8	13.7	15.7	4.5
Sealer	7.0	11.7	41.2	7.0	14.7	19.1	18.0	
Toluene replacement thinner	6.7		55.5	17.5 (Toluene)			9.0	18.0
Xylene replacement thinner	6.5		56.5	7.5	24.0		12.0	

Source: *Air Pollution Control Manual.* 2nd Ed., AP-40. EPA. May 1973.

Figure 10. Examples of Surface Coating and Added Thinner Formulas on an As-Purchased Basis Having Conforming Solvent Systems

INCREASING SOLIDS IN EXISTING COATING FORMULATIONS

An obvious step in reducing solvent emissions is to increase the solids content of existing coating systems.

Advantages

In addition to reduced solvent emissions, particularly during application and air drying, the benefits include:

- Reduced inventory space for drums. Drums of solvent-based coating typically weigh 400 pounds. The following chart shows the effect of reducing solids in a coating formula in a plant that consumes 1,200 dry pounds of coating per day.

Wet Weight Per Drum	% Solids	Dry Weight Per Drum	Drums Per Day
400	30	120	10
400	60	240	5

  Thus, a 100-percent increase in solids made possible a 50-percent reduction in drum storage area.

- Reduced drum handling by operators. Increased solids per drum would also reduce the number of drum changes at the coater, freeing operators for other tasks.

- Reduced energy for removing solvents. Changing from a 30- to 60-percent solids system reduces by almost half the total solvent load that must be removed. Normally, however, to achieve such a high percent of solids more polar or higher-potency solvents must be used. These would typically have slightly higher heats of vaporization than hydrocarbon solvents. Using typical values, we see the effect of a change in solids on heat required to remove the solvent:

% Solids by Weight	% Solvent by Weight	Avg. Heat of Vaporization of Solvent Btu/lb.	Heat Required to Volatilize Solvent from 1,200 lbs. of Dry Coating
30	70	160	448,000
60	40	200	160,000

  The change has resulted in a potential energy savings of almost 300,000 Btu. Additional data on energy savings are given in Figure 11.

Operation	Solvent Base Thermoset Acrylic (Baking temperature - 350°F)	High Solids Polyester (Baking temperature - 350°F)	80% Solids Urethane (Baking temperature - 180°F)
Spray booth	233,280	233,280	233,280
Heat metal	466,100	466,100	183,110
Other heat losses	231,840	231,840	91,080
Oven exhaust	879,984	94,651	37,184
Total Btu required for processing	1,811,204	1,025,871	544,654

NOTE: For these calculations it was assumed that the average yearly temperature was 52°F and that .018 Btu will raise one cubic foot of air 1°F at 100% efficiency.

Source: *Modern Paint and Coatings*, March 1975.

Figure 11. Energy Requirements for Comparable Operations (Btu per hour)

- Increased potential for compliance with emission guidelines. The lower the emissions from any part of the coating operation, the more likely that the plant will be in compliance with emission restrictions. Care must be used in making formula changes, however, to use solvents with emissions that are less photochemically active.

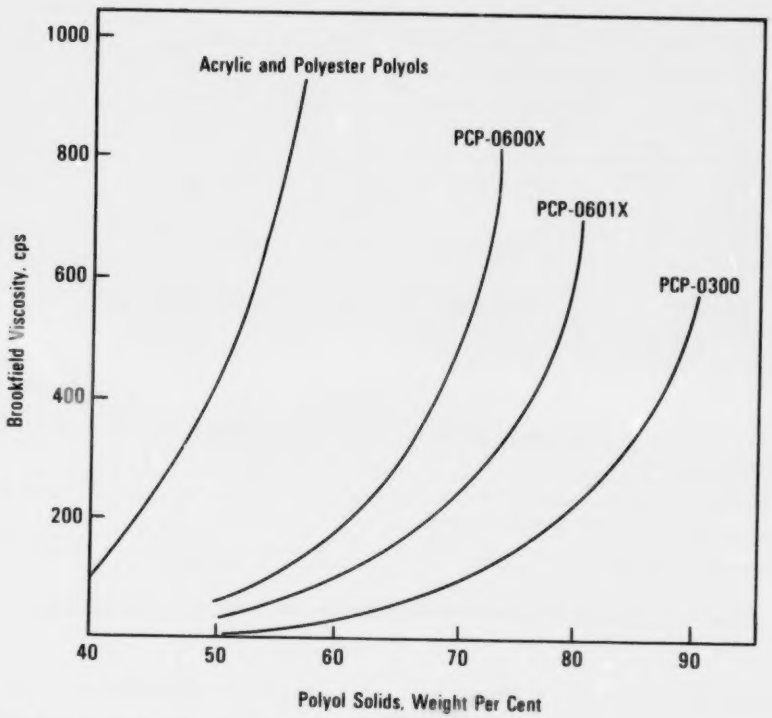
- Reduced freight costs. Freight costs can easily be 2 cents per pound of gross weight, with empty drums themselves weighing about 50 pounds. In the example below, the freight cost for 1,200 pounds of dry coating would be reduced as follows by a 100-percent increase in solids.

Coating Solids	Pounds of Coating Purchased	Total Drum Wt.	Total Wt.	Freight Costs
30%	4,000	400	4,400	$88
60%	2,000	250	2,250	$45

Problems

There are, however, certain drawbacks to high-solids systems, including:

- Higher viscosity of the coating system. As solids are increased, so is the viscosity of the formula. Typical increases in viscosities as a function of the solid content for prepolymer coatings are given in Figure 12. Higher application viscosity may be handled by either equipment or operational changes. An increased coating temperature, for example, may reduce viscosities enough so that the higher-solids system can be run on the same equipment.



Source: *Modern Paint and Coatings,* March 1975

Figure 12. Solids vs. Viscosity for Caprolactone, Acrylic, and Polyester Polyols

- Reduced storage stability. The higher the percentage of solids, the harder it becomes to maintain a stable system. Skinning-over becomes more of a problem with higher solids, with redispersal more difficult. The tendency to thicken or gel with time can often be counteracted by additives, but these may have deleterious effects on other coating properties.
- Less latitude with in-plant formula modifications. Because of the instability of high-solids systems described above, it is usually difficult to modify them in-plant.

Some typical formulas for high solid coatings are presented in Figure 13.

SWITCHING TO WATERBORNE SYSTEMS

Use of water-based coating systems is still a further choice of formula variations for emission control.

Advantages

Differences between emissions from waterborne systems and solvent-based systems are shown in Figure 14. For instance, at 30-percent coating solids, a waterborne system containing 20 percent solvent and 80 percent water would have one-quarter of the solvent emissions of a 100-percent solvent system.

High-Solids Coating (White) (80% Solids)
Urethane

Materials	Total Weight	Solids Weight
Component I		
Multron R-221[1]	94.5	94.5
2-Ethyl-1,3 hexanedial[2]	94.5	94.5
R-966, TiO_2[3]	280.0	280.0
Modaflow, 10% in ethylglycal acetate[4]	10.4	
FC 430, 10% in ethylglycal acetate[5]	15.6	
EAB 381-1/10, 10% in ethylglycal acetate[6]	10.4	1.0
Dibutyltin dilaurate, 10% in ethylglycal acetate[7]	0.5	
Ethylglycal acetate	163.1	
Component II		
Desmodur N-100[1]	331.0	331.0
	1,000.0	801.0

High-Solids Acrylic Hard Enamel

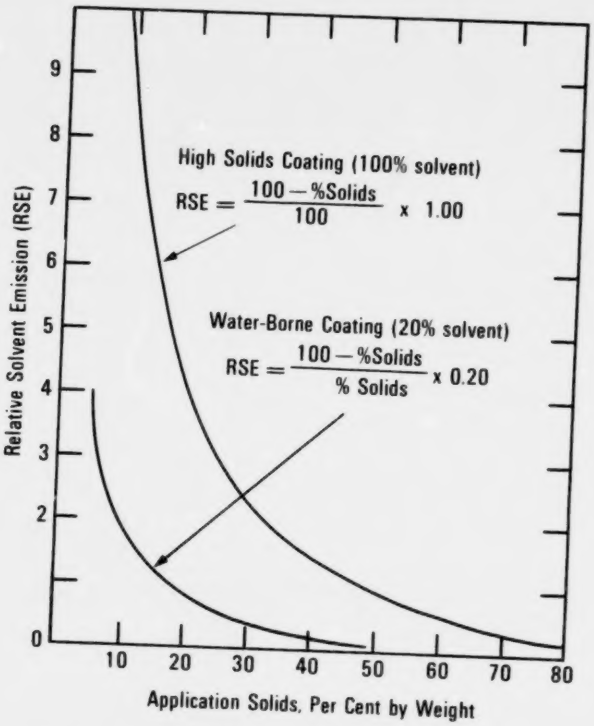
Materials	Parts By Weight
Disperse on roller mill	
Titanium dioxide	60.0
Experimental Resin QR-542 (80% in Ektasolve EE acetate)	40.0
Letdown	
Mill paste (above)	100.0
Experimental Resin QR-542 (80% in Ektasolve EE acetate)	24.2
Cymel 301	22.0
p-TSA (30% in sopropanol)	0.5
n-Butyl acetate	14.4
n-Butanol	11.9
	173.0

Formulation Constants	Percent of Formula
Solids content	77
Titanium dioxide (45%)	
Binder (55%)	
Experimental Resin QR-542 (70%)	
Cymel 301 (30%)	
Volatiles content	23
Catalyst, p-TSA (on binder)	0.2
Spray viscosity, #4 Ford cup (sec) 35	

1. Mobay Chemical Corp.
2. Union Carbide Corp.
3. E. I. duPont de Nemours & Co.
4. Monsanto Co.
5. 3M Co.
6. Eastman Chemical Products, Inc.
7. M & T Chemicals, Inc.

Source: *Modern Paint and Coatings,* March 1975.

Figure 13. Examples of Modern Formulas for High-Solids Systems



Source: *Modern Paint and Coatings,* March 1975.

Figure 14. Relative Emissions of a Hypothetical Waterborne System Containing 20% Solvent and of a Conventional Solvent Base System

Figure 15 further illustrates the reduction in emissions from the substitution of waterborne coatings for conventional or high-solids systems.

Additional advantages of switching to a waterborne system include:

- Reduction of flammability levels. While many waterborne formulations include "co-solvents," these often evaporate before heat treatment, considerably reducing problems in the ovens. Much lower dilutions are required due to the lower percentage of solvent and also to the "quenching" effects of the water vapor.
- Increase in usable polymers. In solvent-based systems, relatively few monomers or prepolymers can be used because of solubility, viscosity, and related factors. In particular, the molecular weights are severely restricted. This affects the ultimate properties of the coating. In waterborne coatings, the choice of monomers and/or prepolymers is much wider.
- Higher-solids content at equivalent viscosity. In solvent polymerizations, as the molecular weight increases so does the viscosity. Waterborne systems are not as sensitive to viscosity from increased molecular weight. Thus, to obtain

Paint System	% N.V.V.*	Volume Ratio: Total Non-Volatile/ Organic Volatile	Ml of Organic Volatile Liberated per Sq Ft per Mil of Dry Film Coating
1. High-solids polyester	80	80/20	0.59
2. Coil-coating polyester	51	51/49	2.30
3. High-solids alkyd	80	80/20	0.59
4. Short-oil alkyd	34	34/66	4.75
5. Water-reducible polyester	48	82/18	0.51
6. Water-reducible alkyd	29	67/33	1.16
7. High-solids water-reducible conversion varnish	80	90/10	0.24
8. High-solids water-reducible conversion varnish	73.5	90/10	0.24
9. High-solids water-reducible conversion varnish	67	90/10	0.24

*Non-volatile by volume.

Source: *Modern Paint and Coatings,* March 1975.

Figure 15. Comparison of the Amount of Organic Volatile Material Contained in High-Solids, Water-Soluble, and Conventional Paints

similar molecular weights, a solvent system must be used with a much higher viscosity than that of a waterborne system. In addition, waterborne system viscosities are less sensitive to solid contents than are those of solvent systems. Thus, waterborne systems permit the use of higher solids with higher molecular weight for the same required viscosity.

- Lower raw material cost. The cost of solvent coatings includes the price of the solvent, whereas in aqueous-based coatings very little solvent is used and the water is free. A typical example follows of raw material costs for equivalent solids systems, in which the solids cost 50 cents per pound and the solvent an average of 75 cents per gallon, or 10 cents per pound.

	Cost of Solids per 100 lb.	Cost of Solvent	Total Raw Material Cost
40% Solids, solvent-based	$20.00	$6.00	$26.00
40% Solids, water-based	$20.00	$1.50	$21.50

The cost of the solvent will be reflected in the selling price of the coating. This was a prime factor in the significant cost increases of solvent-based coatings during the recent petrochemical shortage.

- Ease of clean-up. Water-based systems can be readily cleaned up with water, whereas solvent systems require solvents.

Problems

Drawbacks associated with switching to waterborne coatings include:

- Use of a comparatively untried technology. The traditional reliance on solvent-based systems for metal coating has resulted in a lower level of interest in waterborne systems. However, many authors claim that dry-film properties have been developed that are equal or superior in every respect to those achieved by conventional solvent systems.
- Higher total-system energy requirements to remove water. Water has a higher latent heat of vaporization (1,000 Btu/lb.) than most solvents (100-200 Btu/lb.). Thus, it takes more heat energy to evaporate or remove a pound of water than a pound of solvent. A comparison follows of two systems, one a 70-percent solids solvent coating and the other a 70-percent solids aqueous coating.

Coating Type	Volatiles	Latent Heat of Vaporization Btu/lb.	Heat Required to Volatilize 1,000 lbs. Volatiles
Solvent	Solvents	200	200,000 Btu
Aqueous	Water	1,000	1,000,000 Btu

As a rule of thumb, at $1.25 per 1,000 cubic feet of gas and 1,000 Btu per cubic foot, the cost of natural gas is $1.25 per 1,000,000 Btu. Thus, evaporating the solvent costs 25 cents and the water $1.25.

There may be compensating factors for the high cost of water removal, however, in that some of the solvent that evaporates from waterborne coatings may be used for heating requirements through burning of the oven exhaust gases. This depends on individual plant operations and will be discussed again later.

The higher energy requirement for evaporating the water is usually mitigated by the fact that this constitutes only part of the heat loss of the oven; the exhaust gases also carry away a portion of the heat requirement. Figure 16 compares the energy balance in an oven curing a conventional solvent system and an equivalent waterborne coating that has a solvent component representing 20 percent of the volatile load. In this instance the heat requirements are quite similar, with a 10-percent edge in favor of the waterborne system.

EXHAUST RATES

Solvent Coating

$$\left(\frac{17.5 \text{ gallons of solvent}}{\text{hour}}\right)\left(\frac{10{,}000 \text{ cubic feet at } 70^{\circ}\text{F.}}{\text{gallon}}\right)\left(\frac{1 \text{ hour}}{60 \text{ minutes}}\right)$$

= 2925 cubic feet of air at 70°F. per minute.

The exhaust rate for the solvent system is 2,925 cubic feet of air at 70°F per minute.

Waterborne Coating

A. Solvent Requirement

$$\left(\frac{17.5 \text{ gallons}}{\text{hour}}\right)(0.2)\left(\frac{10{,}000 \text{ cubic feet of air at } 70^{\circ}\text{F.}}{\text{gallon}}\right)\left(\frac{1 \text{ hour}}{60 \text{ minutes}}\right)$$

= 583 cubic feet of air at 70°F. per minute.

B. Humidity Requirement

$$\left(\frac{17.5 \text{ gallons}}{\text{hour}}\right)(0.8)\left(\frac{5{,}000 \text{ cubic feet of air at } 70^{\circ}\text{F.}}{\text{gallon}}\right)\left(\frac{1 \text{ hour}}{60 \text{ minutes}}\right)$$

= 1167 cubic feet of air at 70°F. per minute.

The total exhaust requirement is 1,750 cubic feet of air at 70°F. per minute.

Solvent System

Parts and Conveyor Load

$$Q_m = \left(\frac{11{,}000 \text{ pounds}}{\text{hour}}\right)\left(\frac{0.12 \text{ Btu}}{\text{pound } ^{\circ}\text{F.}}\right)(350^{\circ}\text{F.}-70^{\circ}\text{F.})$$

= 370,000 Btu/hour.

Panel Loss Load

$$Q_p = (10{,}000 \text{ square feet})\left(\frac{0.3 \text{ Btu}}{\text{sq. ft. } ^{\circ}\text{F.}}\right)(350^{\circ}\text{F.}-70^{\circ}\text{F.})$$

= 840,000 Btu/hour.

Figure 16. Heat Requirements for the Baking of Equivalent Solvent-Borne and Waterborne Coatings

Exhaust Load

$$Q_a = \left(\frac{\text{2925 cubic feet at 70}^{\circ}\text{F.}}{\text{minute}}\right)\left(\frac{\text{0.075 pounds}}{\text{cubic foot}}\right)\left(\frac{\text{0.24 Btu}}{\text{pound }^{\circ}\text{F.}}\right)$$

$$\left(\frac{\text{60 minutes}}{\text{hour}}\right)(350^{\circ}\text{F.} - 70^{\circ}\text{F.}) = \text{855,000 Btu/hour.}$$

Total 2,095,000 Btu/hour.

The total heat lost, i.e., the total heat input, is approximately 2,100,000 Btu per hour, which can be supplied by burning 2,100 cubic feet of natural gas per hour.

Waterborne System = 350° Bake

Parts and Conveyor Load

$$Q_m = \left(\frac{\text{11,000 pounds}}{\text{hour}}\right)\left(\frac{\text{0.12 Btu}}{\text{pound }^{\circ}\text{F.}}\right)(350^{\circ}\text{F.} - 70^{\circ}\text{F.})$$

$$= \text{370,000 Btu/hour.}$$

Panel Loss Load

$$Q_p = (\text{10,000 square feet})\left(\frac{\text{0.3 Btu}}{\text{sq. ft. }^{\circ}\text{F.}}\right)(350^{\circ}\text{F.} - 70^{\circ}\text{F.})$$

$$= \text{840,000 Btu/hour.}$$

Water Evaporation Load

$$Q_w = \left(\frac{\text{14 gallons of water}}{\text{hour}}\right)\left(\frac{\text{8.33 pounds}}{\text{gallon}}\right)\left(\frac{\text{1,178 Btu}}{\text{pound }^{\circ}\text{F.}}\right)$$

$$= \text{138,000 Btu/hour.}$$

Exhaust Load

$$Q_a = \left(\frac{\text{1,750 cubic feet at 70}^{\circ}\text{F.}}{\text{minute}}\right)\left(\frac{\text{0.075 pounds}}{\text{cubic foot}}\right)\left(\frac{\text{0.24 Btu}}{\text{pound }^{\circ}\text{F.}}\right)$$

$$\left(\frac{\text{60 minutes}}{\text{hour}}\right)(350^{\circ}\text{F.} - 70^{\circ}\text{F.})$$

Total: 530,000 Btu/hour

1,878,000 Btu/hour

The total heat lost, i.e., the total heat input, is approximately 1,900,000 Btu per hour, which can be supplied by burning 1,900 cubic feet of natural gas per hour.

Source: Metal Finishing, December 1975.

Figure 16 (continued)

- Rust and corrosion potential. Coating applicators, tunnels, and ovens would now be subject to water vapor, which could condense and drip down onto moving parts. Ovens made of galvanized steel may be subject to water corrosion.
- Increased treatment of metal parts before coating. Most metal parts have films of grease and oil that must be removed to achieve proper coating films. Solvent-based coatings have an ability to "self-clean" some of the surface if it has not been completely treated. Water-based coatings, however, would require a completely oil-free surface, which might increase pretreatment costs.
- Slow drying at high humidity. Coating operations that depend primarily on removal of volatiles during application and air drying will be slowed down on days of high humidity and slow water evaporation.

SWITCHING TO ULTRAVIOLET OR ELECTRON BEAM CURE SYSTEMS

Ultraviolet (U.V.) or electron beam systems rely on the rapid uptake of high-intensity energy from an external source to polymerize the low-molecular-weight components of the coating. The materials are supplied at close to 100-percent solids so that, except for extraneous matter, all that is applied in the first place remains in the coating.

Advantages

Benefits of using these systems include:

- Substantial emission reduction. The systems are inherently 100-percent solids, or 100-percent active. Emissions are only incidental and can be as little as 5 percent by weight. There is ozone from the U.V. process, but this can be minimized by proper controls.
- High-speed reactions. Relative typical cure times for total-solids coatings would be:

Curing System	Time
Electron beam	1 second or less
Ultraviolet	seconds
Oven	minutes

- Low operating costs. Figure 17 is a synopsis of operating-cost comparisons for conventional, U.V. and electron beam curing. Figure 18 compares the costs of U.V. curing vs. infrared curing. This is of particular interest, since infrared ovens can be readily converted to U.V. units.
- Reduced floor space for coater. Ovens normally take up much of the floor space in coating lines. A system with U.V. of electronbeam curing that requires minimum oven capacity will use less floor space.

	Heat			U.V.			Electron Beam		
Line Speed (fpm)	60	120	180	60	120	180	60	120	180
Beam Power	--	--	--	3.7*	7.4	11.1	1.25**	2.5	3.75
Machine Power (kW)	2900^+	5800	8800	100	200	300	8	10	12
Power Costs ($/hr)	13.13^o	26.25	39.38	2.00●	4.00	6.00	.16●	.20	.24
Maintenance ($/hr)	.80	1.00	1.20	1.00	2.00	3.00	2.25	2.50	2.75
Nitrogen Gas	--	--	--	--	--	--	1.00	1.50	2.00
Water	--	--	--	--	--	--	.20	.20	.20
Total Costs ($/hr)	13.93	27.25	40.58	3.00	6.00	9.00	3.61	4.40	5.19

---

* Based upon an ultraviolet cure requirement of 1 j/cm^2.

** Based upon an electron beam dose to cure of 2.5 megarads (0.25 j/cm^2 for a 1 mil coating).

+ Based upon natural gas at 1000 BTU/cubic foot and converted directly using 1055 j/BTU.

o Based upon gas costs at $1.25/1000 cubic feet.

● Based upon power costs at 2¢/kWhr.

Source: "Status of Electron Beam Curing," Paper presented at the National Coil Coaters Association Meeting. Las Vegas, May 1971. (Cost figures updated)

Figure 17. Comparative Economics of High-Speed Curing Units

	Typical U.V.	Typical IR
Oven length (ft)	10	90
Line speed (fpm)	60	60
Vehicle	Polyester	Urea-alkyd
Nonvolatile (%)	90-100	35-65
Film thickness (mils)	2	2
Coverage (wet) (sq ft/gal)	700-800	500
Coats	1	2
Cure time (sec)	10	90
Exit temp (°F)	100	130
Cool	No	Yes
Cost of system ($/gal)	5.00-6.00	2.00-3.00
Cost per sq ft (¢)		
Per coat	0.7-0.9	0.9-1.3
Total	0.7-0.9	1.8-2.6
Power (kW)	100	250
Power per sq ft (¢)	Less than 0.1	App. 0.2 (2 coats)

Source: *Journal of Paint Technology,* Vol. 44, No. 571, Aug. 1972.

Figure 18. Comparative Costs of U.V. Curing and Infrared Curing

Problems

The disadvantages of switching to U.V. or electron beam curable coatings systems are:

- High formula costs. As can be seen in Figure 18, formulas based on the types of polymers that can be cured by U.V. or electron beam cost several times as much as conventional coatings, necessitating tight control on overcoating and waste.
- Limited selection of polymers. Since this is a relatively new technology, the range of polymers available is still limited, although some can coatings, varnishes, and inks have been developed.

- Special precautions for high intensity energy sources. U.V. and electron beam energy sources can cause injuries to workers if not carefully shielded and operated.
- High costs of coating and curing equipment. Initial capital expenditures for coaters, curing chambers, and protective shielding tend to be higher than equipment for conventional coatings.

SWITCHING TO 100-PERCENT SOLIDS COATINGS

Total-solids systems represent an entirely different technology and for most applications require new equipment that is generally not compatible with existing lines. Because of the potential advantages, however, the automotive industry has begun using some of these coatings for auto bodies. Further, chain-link fencing is processed with a "green" coating, and many houseware items have protective plastic coatings.

Advantages

Benefits of using 100-percent solids coating systems include:

- Freedom from emissions. There is no solvent vapor generated in the curing process for total-solids coatings. Emissions are therefore negligible and are limited to solid particles that can be trapped by relatively cheap systems like dust collectors.
- Reduced energy consumption. Since the coating is 100-percent solids, no heat is required to volatilize solvent or water. The only heat needed for thermoplastic coatings is that necessary to melt or flux the material so that it will bond to the surfaces.

Heats of fusion or melting tend to be lower than heats of vaporization, so that the net heat required per 100 pounds of dry coating would be less than that for either the high-solids or aqueous systems. Additional heat will be needed to cure the coating if it is a thermosetting type; however, since no solvent or water has to be removed, the total heat will still be lower than for an equivalent waterborne or high-solids solvent system.

Problems

Disadvantages of 100-percent solids coating systems are:

- Higher costs. On a relatively equivalent basis, solvent-based paints were approximately 1 - 1.3 cents/ft^2/mil of thickness, whereas fluidized-bed powder coatings were 1.6 - 4.1 cents/ft^2/mil, depending on the system.
- Limited selection of systems. Only certain polymers are available in a form that will flux and fuse (polyamides, polyesters, and some epoxies), limiting total-solids coating formulations.

- Variable adhesion. Adhesion, a direct function of the fusion process, may be adversely affected by any irregularity in temperature in either a 100-percent solids coating or the surface to be coated.
- Incompatibility with existing coating lines. As mentioned, special new equipment is required for application and curing of 100-percent solids systems.
- Difficulty in applying uniform thin coatings. The total-solids coating technique lends itself to thicker coatings. Applications under 1 mil are difficult; 3 or more mils is more typical.
- Color changes in-process. In 100-percent solids coating lines, large amounts of colored particles must be moved and cleaned up before each color change or the next batch of articles may have off-specification colors or shades.

EMISSION CONTROL THROUGH PROCESS CHANGES

Operating changes that a plant can consider in setting up its emission control program include:

- Controlling emissions by incineration;
- Controlling emissions by adsorption;
- Improving spraying efficiency;
- Improving dip coating, flow coating, and coil coating efficiency;
- Purchasing prefinished roll stock;
- Increasing vapor concentration; and
- Educating plant personnel for process changes.

The first options, controlling emissions by incineration and adsorption, will be covered in Part B of this manual, which deals with treatment of hydrocarbon emissions and heat recovery. Discussion of the remaining process changes follows.

IMPROVING SPRAYING EFFICIENCY

The most commonly used air-spraying method, as explained earlier, is the most inefficient coating method. Overspray (and thus emissions) can often be reduced by ganging spray nozzles of different spray patterns or by rotating the article to be sprayed. Prefinishing the article so only a touch-up is required may also cut spraying losses.

Other techniques for improving efficiency include minimizing manual spraying and color changeovers through production control.

The effect of inefficient spraying on emissions is obvious. More air is required to maintain the TLV, necessitating more fan capacity. If emissions have to be controlled, added cfm are very expensive, as is shown below:

Effect of Overspray Reduction

Coating Formulation	TLV	Overspray	scfm
20/80 Coating system	200 ppm	50%	1,400
	200 ppm	10%	1,080

In this case, the savings in fuel for the afterburner would amount to about $4,000 per year, which would be in addition to a savings of about 27 percent on the cost of the coating system used.

A gross measurement of overspray can be obtained by a material balance between the coating actually used and the coating that is on the articles after spraying.

IMPROVING DIP COATING, FLOW COATING, AND COIL COATING EFFICIENCY

As in all coating operations, control of coating weight or thickness is of primary importance. There are many devices that can be installed on production lines for sampling on a random basis and for weighing the article if it has, for example, been dip coated and can be weighed. Off-weights will trigger either a manual or automatic response to correct the situation. In the case of dip coating, this corrective response might be shorter immersion time, reduced immersion depth, or increased air blow-off pressure.

Beta ray, gamma ray, and x-ray devices have been used in many areas of industry for determining coating thickness on moving webs. Their use in monitoring high-speed coil-coating applications should be considered.

PURCHASING PREFINISHED ROLL STOCK

Some items lend themselves to prefinishing and use of raw materials that come in coil/machinable form. For example, license plate stock is prime-coated at one location and stamped and painted at another. This not only places the prefinishing step in a more efficient setting, but also shifts some of the solvent emission load. Since a final product is still the responsibility of the ultimate finisher, however, precise control must be maintained over the prefinisher.

INCREASING VAPOR CONCENTRATION

The cost of moving and heating air is proportional to the amount of air being moved. There is, therefore, a considerable operating-cost advantage in having vapors as concentrated as possible.

In our initial discussion of basic factors that affect emissions, we pointed out that to maintain a safe TLV, 30 times more air must be supplied to the spray booths or air-drying tunnels than is strictly necessary for a normal rate of evaporation. If booth and tunnel areas can be kept free of operating personnel, however, the TLV concentration requirements can be replaced by the much less demanding 25-percent LEL. Further, operators can continue to work in the areas by using protective devices.

Substitution of automatic spraying wherever possible will eliminate the need to maintain TLV, with important economic advantages. For instance, without TLV strictures the ventilation requirements can be reduced by a factor of about 10, lessening energy needed to move the air or to control its temperature. Moreover, emission control becomes much cheaper because (a) equipment size is drastically reduced, with savings of 40 percent; and (b) fuel costs are also greatly reduced because less air has to be heated and much less fuel is required per scfm.

An important consequence of increasing vapor concentrations is that all equipment conveying wet parts must be enclosed. However, the economic advantages of increased concentrations may pay for the substantial modifications that enclosure requires.

Vapor concentrations cannot be raised beyond safe limits or the limits placed on recovery incineration equipment. For example, if emissions are controlled by combustion with either an afterburner or catalytic converter, there is no point going above 40 percent LEL; because of the considerable heat value of most solvent vapors, particularly hydrocarbons, severe overheating and equipment damage may result from excess vapor combustion. Indeed, this is reported to be one of the most frequent problems with afterburners, especially with catalytic units.

EDUCATING PLANT PERSONNEL FOR PROCESS CHANGES

The main problem in switching to a more efficient application method (without significant change in system formula) may be human resistance to change. This is particularly true where hand operations are replaced by automated methods. A change that may even temporarily affect quality or production rate may be resisted by supervisory personnel who pride themselves on high-efficiency/low-downtime operations. Therefore, any test of new equipment (for instance, airless or electrostatic) should be closely supervised by management-level staff.

A second problem is that a new process often involves new materials with higher costs per pound. Economic advantage can be achieved only if the product is used at the prescribed rate, restricting the operating personnel's latitude in applying the coating. Previously, if the coating was within 10 - 20 percent of desired weight or thickness, there was little cost effect. Higher costs per pound necessitate more precise control.

Management must make it clear to employees that the changes are in everyone's best interest.

SUMMARY

In Part A of this volume, we have covered the basic terms connected with pollution control, the properties of solvents that can cause pollution, and the ways that materials and processes influence the amount of emissions.

We have seen that the factors most affecting emissions are:

- Total volume or weight of coating used;
- Efficiency of application; and
- Composition of the formulas used.

Many routine opportunities for pollution reduction will become evident in a simple but thorough survey of the plant. Some possibilities may be beyond one department's direct control, but cooperative effort with other sections may enable considerable reductions in pollution and costs.

PRODUCT DESIGN CONSIDERATIONS

Certain variables in design should be studied as possible aids to pollution control. Managers should consider:

- Choosing material that will serve the intended use without painting, for instance, anodized aluminum, plastic, or plated components;
- Standardizing and reducing the number of colors to minimize solvent needed for clean-up between color changes and to reduce inventory;
- Tightening specifications on coating thicknesses or number of coats required; and
- Eliminating pockets, rough coatings, or other features that require large amounts of paint for adequate coverage.

FABRICATION CONSIDERATIONS

Manufacturing variables that may aid in pollution control include:

- Using precoated stock and limiting painting operations to touch-up of damage occurring during fabrication;
- Buying primed components and applying only a top coat;

- Increasing protection, and saving paint, by using conversion coatings such as anodizing and phosphatizing;
- Assembling first and saving painting for the final step, to avoid two paint applications; and
- Fabricating the articles and then subcontracting the coating operation to a finisher who already has emission controls in place.

PROCESS CONSIDERATIONS

We have discussed in some detail the process changes that can be made to reduce emission levels in coating operations. Those that will have a high impact on lowering emissions at the source include:

- Replacing manually operated, air-atomized spray methods with, preferably, a combination of airless and electrostatic spraying, to reduce overspray and help reduce ventilation needs;
- Converting to formulas with as high a solids content as possible;
- Switching wherever possible to waterborne coating;
- Reducing excessive ventilation;
- Using powder coating and U.V. curing, where feasible, when new facilities are installed.

If control devices prove necessary even after all possible design, manufacturing, and process changes have been made, plant management should carefully examine the total air balances in the facility and should study all unavoidable sources of emission, with a view to increasing concentrations in waste streams.

The end-of-line treatment of these waste streams will be the subject of Part B, which follows.

Part B

TREATMENT OF HYDROCARBON EMISSIONS AND HEAT RECOVERY

CHAPTER I

DISPOSAL OF SOLVENT VAPORS

Most plants have hydrocarbon emissions that cannot be eliminated by the source control methods discussed in Part A. There are a number of techniques for treating these emissions, of which the most widely used are based on combustion that breaks down organic pollutants into other, nonpollutant substances.

COMBUSTION

Combustion of organic compounds is a widely used technique for air pollution emissions control. At a high enough temperature, carbon and hydrogen will combine with oxygen to produce carbon dioxide and water. Although there is some concern over accumulation of carbon dioxide in the atmosphere, both CO_2 and water will probably remain classified as nonpollutants for the foreseeable future.

Elements other than carbon and hydrogen that may be present in the organic compound will also be released (though not necessarily in oxygenated form) in the combustion process. Halogenated hydrocarbons like chlorine and fluorine are generally converted to the acids, though in certain cases phosgene may result. Sulfur is burned to sulfur dioxide, while nitrogen is converted to nitric oxide.

Combustion is used for control of odorous sulfur and nitrogen compounds where the amounts of SO_2 or NO formed are too small to cause significant air pollution. However, halogenated compounds are not normally burned, because of the extremely corrosive and hazardous nature of the gases formed. Even trace quantities of HCl or HF would force the use of exotic and expensive corrosion-resistant materials in the control equipment. Greater-than-trace quantities would require additional controls for the removal of acid gases. Thus, combustion for the control of halogenated hydrocarbons is impractical.

In a recent review of solvent metal cleaning practices in industry,* Dow Chemical Company found that halogenated hydrocarbons are used almost exclusively in vapor degreasing and in about half of the cold degreasing operations. From a practical standpoint, therefore, solvent combustion as an air pollution control technique is limited largely to the metal coating industry.

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*"Study to Support New Source Performance Standards for Solvent Metal Cleaning Operations." Report to EPA by The Dow Chemical Company, June 1976.

Combustion of solvent vapors can be accomplished in one of three ways:

- Direct-flame incineration
- Catalytic incineration
- Process boilers

DIRECT-FLAME INCINERATION

Direct-flame or thermal incineration involves raising the waste gas temperature and sustaining it long enough for any hydrocarbons present to combine with available oxygen. A direct-flame incinerator usually consists of a burner fueled with auxiliary fuel and a mixing chamber. The efficiency of the unit depends on the temperature and residence-time characteristics of the unit and, to a lesser degree, the solvent burned and the design details.

Eighty-five percent combustion of most contaminants is easily obtainable at temperatures of 1200°F - 1400°F and 95 percent at approximately 1500°F. For direct-flame units without heat recovery, the principal expense is fuel. The addition of heat-recovery equipment will increase capital costs but reduce those for fuel.

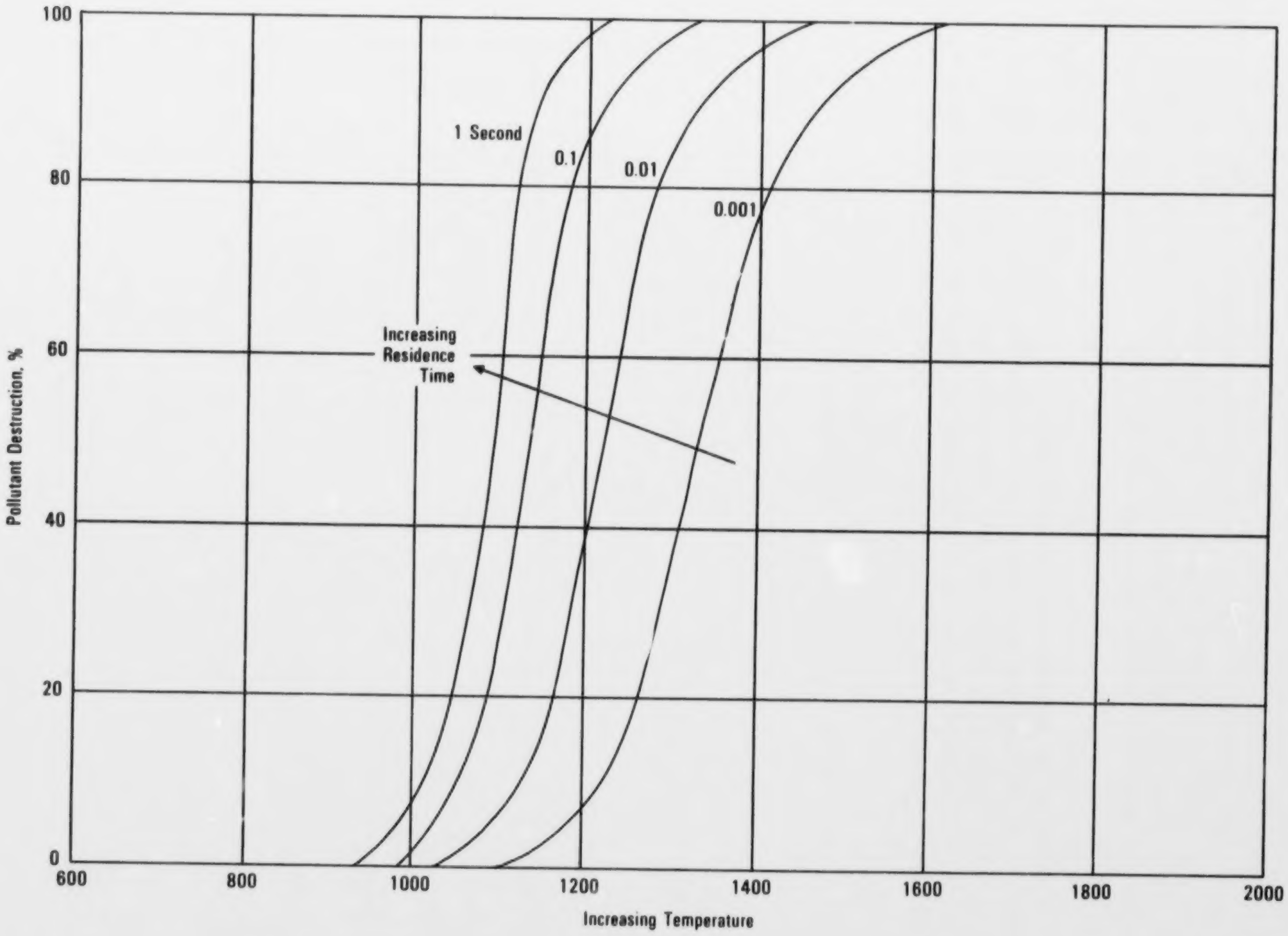
Gas Conditioning

Any non-combustible material, such as particulate matter in the waste gas, will simply pass through the incinerator at normal temperatures. Since the gas velocities are generally lower in the combustion chamber than in the incoming ductwork, the combustion chamber will act as a settling chamber and dust will tend to accumulate there. This does not normally affect the performance of the unit unless the buildup significantly reduces the combustion chamber volume or alters the flow pattern. Where the incinerator exhaust is circulated back into the oven, the presence of particulate matter may affect the quality of the coating.

In most metal coating operations, the carryover of particulate matter is insignificant and no prior conditioning or precleaning is necessary. Where large amounts of paint are likely in the exhaust gas, a dry-type collector is preferred to avoid cooling of the gases and increased incinerator fuel consumption.

Combustion Conditions

To achieve efficient combustion of hydrocarbons to carbon dioxide and water, the solvent must be mixed with sufficient oxygen held at a uniform temperature of between 1200°F and 1500°F for 0.3 - 0.5 seconds. Time and temperature are interrelated, so that a relatively short contact period and high temperature can produce an efficiency (i.e., degree of pollutant destruction) equivalent to a time/temperature unit with long contact and low temperature. This effect is illustrated in Figure 1. For normal straight-chain solvents, operating temperatures of from 1200°F to 1300°F at a residence time of 0.3 - 0.5 seconds are generally used to achieve greater than 90 percent control. Methane, cellosolve, or benzene-based compounds, however, may require a temperature of 1400°F - 1500°F at conventional contact periods of 0.3 - 0.5 seconds.

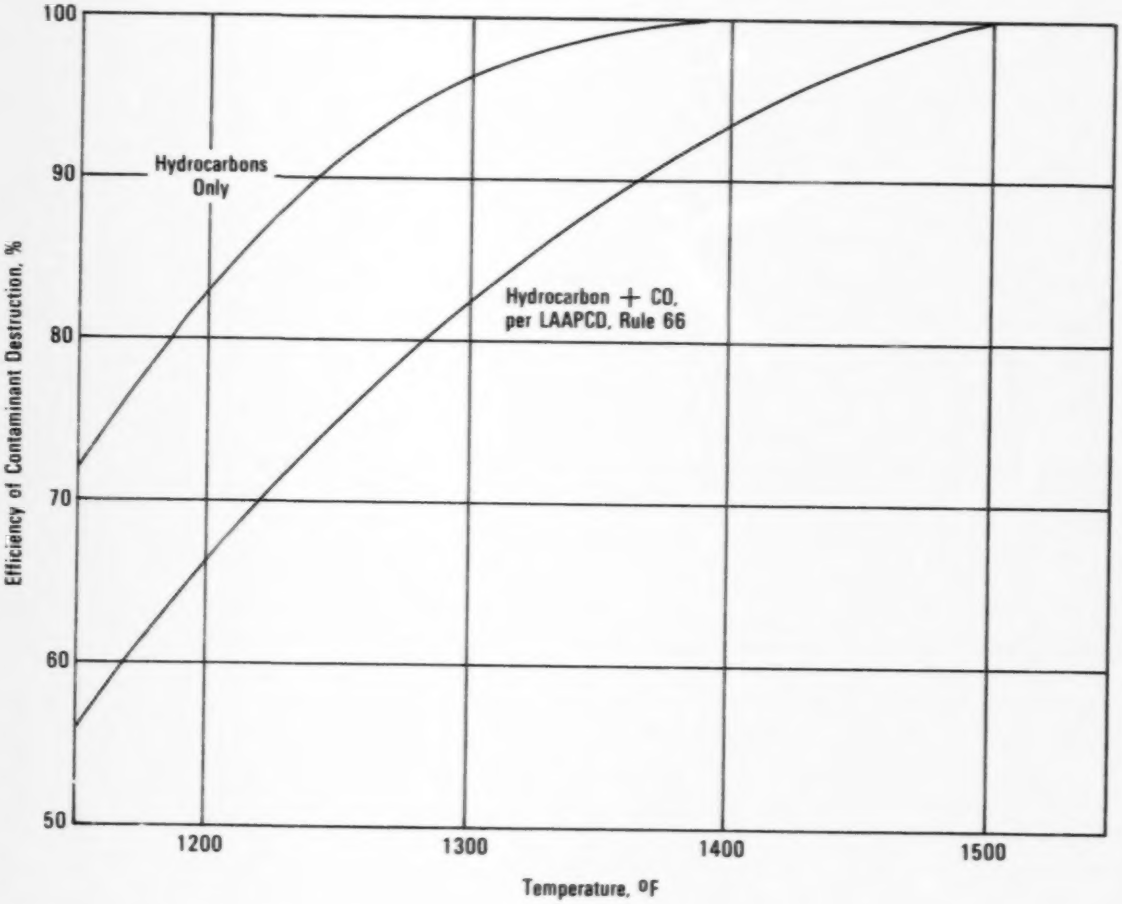


Source: *Afterburner Systems Study*, Shell Development Company, 1972.

Figure 1. Coupled Effects of Temperature and Time on Rate of Pollutant Oxidation

In cases where carbon monoxide formation in the incinerator is deducted from the unit's efficiency, such as under Rule 66 of the Southern California Air Pollution Control District referred to earlier, significantly higher time/temperature units are required to achieve a given efficiency. This principle is illustrated in Figure 2. The combustion of organic carbon to carbon dioxide is a two-stage reaction: the first stage of oxidation to CO involves a relatively high-heat release and proceeds rapidly. The second stage, further oxidation to CO_2, gives off less heat and is therefore an inherently slower reaction.

The zone of combustion consists of a region of rising temperature followed by a dwell region with an essentially constant temperature. The design residence time of 0.3 or more seconds should apply to the reaction zone only, with additional volume provided for initial combustion and mixing. Insufficient combustion chamber volume is probably the most significant design flaw in units that fail to meet performance expectations.



Source: *Afterburner Systems Study,* Shell Development Company, 1972.

Figure 2. Typical Effect of Operating Temperature on Effectiveness of Thermal Afterburner for Destruction of Hydrocarbons and CO

Thermal design must take into account the following factors:

- Efficiency increases with operating temperature.
- Efficiency increases with detention time of up to approximately one second.
- Efficiency increases with initial hydrocarbon concentration.
- Efficiency decreases if the waste gas is preheated to a point approaching the combustion temperature.
- Efficiency increases with the degree of contact between the flame and the solvent vapors.
- Poor mixing yields low efficiency even if the temperature and residence time are sufficient.
- Carbon monoxide removal requires a minimum temperature of 1300°F regardless of retention time.

Process Design Principles

The process design of a thermal incinerator involves selecting the general characteristics for the unit, establishing design values for temperatures and gas volumes, and determining the fuel-firing rate and combustion chamber volume. Once the process has been fully described, the physical facilities for meeting process requirements can be determined.

The information required for the process design calculations is:

- Inlet gas flow rate, scfm;
- Inlet gas temperature, °F; and
- Solvent type and vapor concentration range, % or ppm.

Where a heat exchanger is used to preheat the gas, the temperature at the incinerator inlet will be greater than the temperature at which the waste gas leaves the process. Heat exchanger design considerations are further described below under Heat Recovery.

The desired gas temperature at the incinerator must be specified. Frequently, air pollution regulations require the gas temperature to be above a certain minimum. This may vary from about 1250°F for easily oxidized solvents to 1500°F for resistant vapors. Where carbon monoxide formation must be prevented, a minimum design temperature of 1400°F is recommended. The desired gas temperature at the incinerator should be slightly in excess of the required minimum.

The residence times of 0.3 - 0.5 seconds mentioned earlier should be considered as minimum values for systems burning hydrocarbon solvents without significant objectionable impurities. Many units are operating satisfactorily at 0.3 seconds residence time, but only where extremely good mixing is achieved. For carbon monoxide removal, the higher residence time of 0.5 seconds should generally be used.

Prior to design of the incinerator, a burner type and fuel should be selected that will be compatible with the source of oxygen for combustion, to the extent that this is known. If the contaminated air stream will be used to provide the oxygen, the size of the incinerator and the heat requirements will be lower, since it will not be necessary to accommodate outside air in the system. Burner types will be discussed presently. Natural gas and propane-fired units use contaminated air almost exclusively. Oil-fired burners may be set up to use contaminated air, but frequently use outside air to avoid fouling of the primary air blower and burner gun.

Hydrocarbon solvents used in metal coating have a high fuel value (Btu per pound of solvent) and will contribute to the heat required for incineration. At concentrations of 100-200 ppm, the fuel saved will be almost negligible, but the savings will be significant beyond 25-percent LEL concentrations. Heat available from the solvent is normally included in the heat balance.

Fuel Requirements

The first step in the design of a thermal incinerator is to determine the amount of fuel required to heat the waste gas stream to the design temperature. The amount of fuel will depend on the flow rate, composition, and temperature of the incoming waste gas, the type of fuel, and whether the oxygen required will be derived from the waste gas or from external air. Any heat value from the solvent vapors in the waste gas stream will reduce the fuel needs.

When a fuel is burned, carbon and hydrogen in the fuel combine with air to produce carbon dioxide and water. The heat energy released raises this carbon dioxide and water to a very high temperature. When air is used as an oxygen source, the nitrogen present must also be heated, lowering the temperature in the gas mixture (approximately 3400°F). If the combustion products are further mixed with a waste gas stream, the temperature of the resultant mixture will be still lower. In a normal design situation, the final desired temperature of the gas mixture is known and the problem becomes one of finding the proper fuel-addition rate.

The potential heat energy released by various organic materials burned at 60°F is termed the gross or higher heat value. Since water is a combustion product of most fuels, the energy available to heat combustion products must be reduced by the heat of vaporization of the water formed. The resultant heat is termed the net or lower heat value. Gross and net heat values, along with combustion air requirements for a number of fuels used in incineration, are shown in Table I. In heating waste gas streams, the net heat released is distributed among the combustion products and the waste gases. Since the ratio of combustion air to fuel is known, calculations are simplified by working with the concept of available heat. This is excess heat remaining for other purposes after the combustion products have been heated to a specified temperature. As may be seen in Figure 3, the available heat is reduced as the design temperature increases, since more heat is consumed in heating the combustion products. If excess air is included with the combustion products, the available heat for other purposes is reduced still further, as is shown in Figure 4. It should be noted that Figure 4 is approximate, in that it is assumed that the ratio of combustion air to heat content is constant for all fuels.

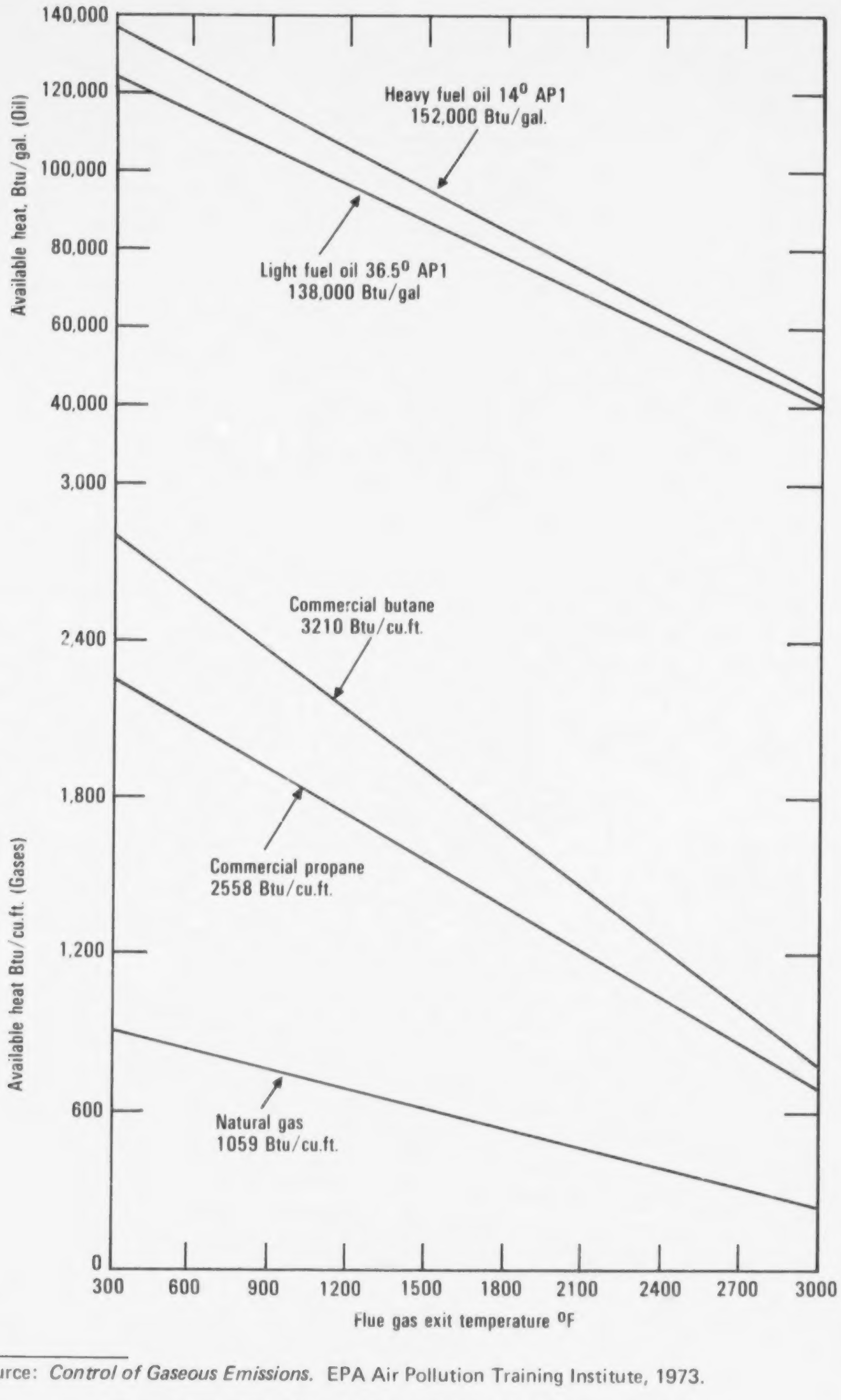
Table I

Combustion Constants

No.	Substance	Formula	Molecular Weight	Lb per Cu Ft	Cu Ft per Lb	Sp Gr Air 1.0000	Heat of Combustion				For 100% Total Air Moles per Mole of Combustible or Cu Ft per Cu Ft of Combustible						For 100% Total Air Lb per Lb of Combustible					
							Btu per Cu Ft		Btu per Lb		Required for Combustion			Flue Products			Required for Combustion			Flue Products		
							Gross (High)	Net (Low)	Gross (High)	Net (Low)	O_2	N_2	Air	CO_2	H_2O	N_2	O_2	N_2	Air	CO_2	H_2O	N_2
1.	Carbon*	C	12.01	—	—	—	—	—	14,093	14,093	1.0	3.76	4.76	1.0	—	3.76	2.66	8.86	11.53	3.66	—	8.86
2.	Hydrogen	H_2	2.016	0.0053	187.723	0.0696	325	275	61,100	51,623	0.5	1.88	2.38	—	1.0	1.88	7.94	26.41	34.34	—	8.94	26.41
3.	Oxygen	O_2	32.000	0.0846	11.819	1.1053	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
4.	Nitrogen (atm)	N_2	28.016	0.0744	13.443	0.9718	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
5.	Carbon monoxide	CO	28.01	0.0740	13.506	0.9672	322	322	4,347	4,347	0.5	1.88	2.38	1.0	—	1.88	0.57	1.90	2.47	1.57	—	1.90
6.	Carbon dioxide	CO_2	44.01	0.1170	8.548	1.5282	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	Paraffin series																					
7.	Methane	CH_4	16.041	0.0424	23.565	0.5543	1013	913	23,879	21,520	2.0	7.53	9.53	1.0	2.0	7.53	3.99	13.28	17.27	2.74	2.25	13.28
8.	Ethane	C_2H_6	30.067	0.0803	12.455	1.0488	1792	1641	22,320	20,432	3.5	13.18	16.68	2.0	3.0	13.18	3.73	12.39	16.12	2.93	1.80	12.39
9.	Propane	C_3H_8	44.092	0.1196	8.365	1.5617	2590	2385	21,661	19,944	5.0	18.82	23.82	3.0	4.0	18.82	3.63	12.07	15.70	2.99	1.68	12.07
10.	n-Butane	C_4H_{10}	58.118	0.1582	6.321	2.0665	3370	3113	21,308	19,680	6.5	24.47	30.97	4.0	5.0	24.47	3.58	11.91	15.49	3.03	1.55	11.91
11.	Isobutane	C_4H_{10}	58.118	0.1582	6.321	2.0665	3363	3105	21,257	19,629	6.5	24.47	30.97	4.0	5.0	24.47	3.58	11.91	15.49	3.03	1.55	11.91
12.	n-Pentane	C_6H_{12}	72.144	0.1904	5.252	2.4872	4016	3709	21,091	19,517	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81
13.	Isopentane	C_6H_{12}	72.144	0.1904	5.252	2.4872	4008	3716	21,052	19,478	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81
14.	Neopentane	C_6H_{12}	72.144	0.1904	5.252	2.4872	3993	3693	20,970	19,396	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81
15.	n-Hexane	C_6H_{14}	86.169	0.2274	4.398	2.9704	4762	4412	20,940	19,403	9.5	35.76	45.26	6.0	7.0	35.76	3.53	11.74	15.27	3.06	.46	11.74
	Olefin series																					
16.	Ethylene	C_2H_4	28.051	0.0746	13.412	0.9740	1614	1513	21,644	20,295	3.0	11.29	14.29	2.0	2.0	11.29	3.42	11.39	14.81	3.14	1.29	11.39
17.	Propylene	C_3H_6	42.077	0.1110	9.007	1.4504	2336	2186	21,041	19,691	4.5	16.94	21.44	3.0	3.0	16.94	3.42	11.39	14.81	3.14	1.29	11.39
18.	n-Butene	C_4H_8	56.102	0.1480	6.756	1.9336	3084	2885	20,840	19,496	6.0	22.59	28.59	4.0	4.0	22.59	3.42	11.39	14.81	3.14	1.29	11.39
19.	Isobutene	C_4H_8	56.102	0.1480	6.756	1.9336	3068	2869	20,730	19,382	6.0	22.59	28.59	4.0	4.0	22.59	3.42	11.39	14.81	3.14	1.29	11.39
20.	n-Pentene	C_6H_{10}	70.128	0.1852	5.400	2.4190	3836	3586	20,712	19,363	7.5	28.23	35.73	5.0	5.0	28.23	3.42	11.39	14.81	3.14	1.29	11.39
	Aromatic series																					
21.	Benzene	C_6H_6	78.107	0.2060	4.852	2.6920	3751	3601	18,210	17,480	7.5	28.23	35.73	6.0	3.0	28.23	3.07	10.22	13.30	3.38	0.69	10.22
22.	Toluene	C_7H_8	92.132	0.2431	4.113	3.1760	4484	4284	18,440	17,620	9.0	33.88	42.88	7.0	4.0	33.88	3.13	10.40	13.53	3.34	0.78	10.40
23.	Xylene	C_6H_{10}	106.158	0.2803	3.567	3.6618	5230	4980	18,650	17,760	10.5	39.52	50.02	8.0	5.0	39.52	3.17	10.53	13.70	3.32	0.85	10.53
	Miscellaneous gases																					
24.	Acetylene	C_2H_2	26.036	0.0697	14.344	0.9107	1499	1448	21,500	20,776	2.5	9.41	11.91	2.0	1.0	9.41	3.07	10.22	13.30	3.38	0.69	10.22
25.	Naphthalene	$C_{10}H_8$	128.162	0.3384	2.955	4.4208	5854	5654	17,298	16,708	12.0	45.17	57.17	10.0	4.0	45.17	3.00	9.97	12.96	3.43	0.56	9.97
26.	Methyl alcohol	CH_3OH	32.041	0.0846	11.820	1.1052	868	768	10,259	9,078	1.5	5.65	7.15	1.0	2.0	5.65	1.50	4.98	6.48	1.37	1.13	4.98
27.	Ethyl alcohol	C_2H_6OH	46.067	0.1216	8.221	1.5890	1600	1451	13,161	11,929	3.0	11.29	14.29	2.0	3.0	11.29	2.08	6.93	9.02	1.92	1.17	6.93
28.	Ammonia	NH_3	17.031	0.0456	21.914	0.5961	441	365	9,668	8,001	0.75	2.82	3.57	—	1.5	3.32	1.41	4.69	6.10	—	1.59	5.51
29.	Sulfur*	S	32.06	—	—	—	—	—	3,983	3,983	1.0	3.76	4.76	SO_2 1.0	—	3.76	1.00	3.29	4.29	SO_2 2.00	—	3.29
30.	Hydrogen sulfide	H_2S	34.076	0.0911	10.979	1.1898	647	596	7,100	6,545	1.5	5.65	7.15	1.0	1.0	5.65	1.41	4.69	6.10	1.88	0.53	4.69
31.	Sulfer dioxide	SO_2	64.06	0.1733	5.770	2.2640	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
32.	Water Vapor	H_2O	18.016	0.0476	21.017	0.6215	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
33.	Air	—	28.9	0.0766	13.063	1.0000	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

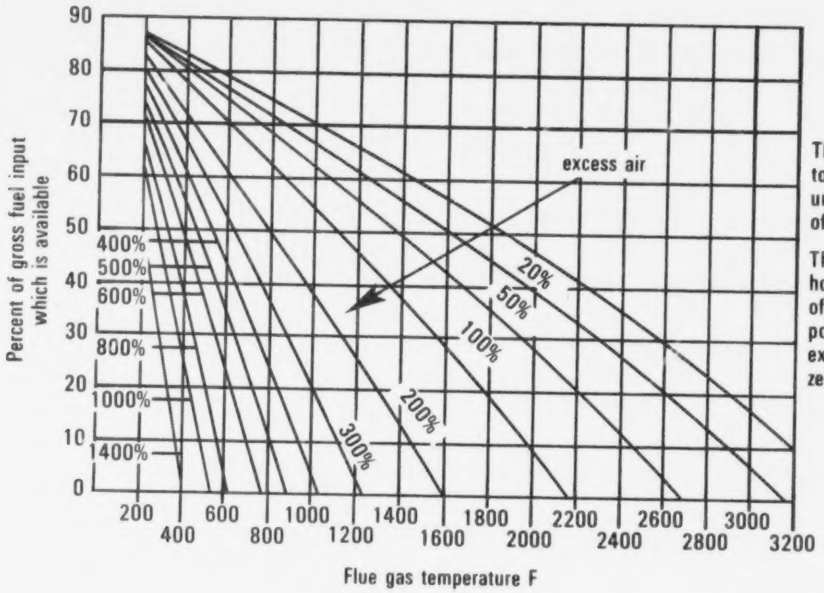
*Carbon and sulfur are considered as gases for molal calculations only.

NOTE: This table is reprinted from *Fuel Flue Gases*, courtesy of American Gas Association. All gas volumes corrected to 60°F and 30 in. Hg dry.



Source: *Control of Gaseous Emissions.* EPA Air Pollution Training Institute, 1973.

Figure 3. Available Heats for Some Typical Fuels (Referred to 60°F)



This chart is only applicable to cases in which there is no unburned fuel in the products of cumbustion.

The average temperatuie of the hot mixture just beyond the end of the flame may be read at the point where the appropriate % excess air curve intersects the zero available heat line.

Source: *Control of Gaseous Pollutants,* EPA Air Pollution Training Institute, 1973.

Figure 4. Generalized Available Heat Chart for All Fuels at Various Flue Gas Temperatures and Various Excess Combustion Air (Referred to 60°F)

When the available heat of combustion is distributed in the waste gas, its temperature will rise. However, this rise is not uniform throughout the combustion range. For this reason, it is common practice to work in terms of enthalpy (heat content) of the gases at various temperatures. Enthalpies of common gases are shown in Table II. As this table shows, raising the temperature of one standard cubic foot of CO_2 from 200°F to 1200°F requires 33.55 - 3.39, or 30.16 Btu.

When the combustion air is drawn from outside the waste gas stream, calculations of fuel requirements are relatively simple; the use of waste gas for combustion requires further data on combustion air requirements. Data needed for computing natural gas or propane requirements are given in Table III; data for oil are presented in Table IV.

Sample computations follow for determining fuel requirements for various design conditions.

Computations for Gas Requirements

Example 1—Given:	3000 acfm of air containing 500ppm of toluene. The air temperature is 300°F.
Find:	The amount of natural gas required to heat the gas stream to 1400°F, assuming that combustion air is drawn from the gas stream and ignoring the fuel value of the solvent.

Since the combustion air is to be drawn from the waste gas stream, it will be necessary to write an equation balancing heat input and consumption in terms of an unknown gas quantity:

1. Heat Input

   = (Available heat at 1400°F at 0% excess air) x G +

   (Credit for preheat of combustion air from 60°F to 300°F)

   where G = scfm of natural gas required.

   - From Table III,
     - Available heat at 1400°F = 668.6 Btu/scf gas
     - Amount of combustion air required at 0% excess air

       = 10.36 scf/scf gas
   - From Table II, for air, enthalpy difference (300°F - 60°F)

     = 4.42 Btu/scf air

2. Heat Consumption

   = (scfm waste gas - scfm required for combustion) x

   enthalpy difference (1400°F - 300°F)

   - scfm waste gas = 300 acfm x $\frac{460 + 60}{460 + 300}$ = 2053 scfm
   - scfm required for combustion = 10.36 x G scfm
   - From Table II, for Air, enthalpy difference (1400°F - 300°F)

     = 26.13 - 4.42

     = 21.71 Btu/scf
   - Thus, heat consumption

     = (2053 - 10.36 x G) x 21.71 Btu/min.

3. Heat Balance: Heat Input = Heat Consumption

   - Thus, 668 x G + 4.42 x 10.36 x G = (2053 - 10.36 x G) x 21.71
   - Solving for G, G = 47.5 scfm natural gas

Example 2—Using the data from Example 1, compute the gas consumption considering the heat available from the combustion of toluene.

Toluene combustion will enter the heat balance by providing a heat input and by reducing the unburned air that must be heated to the design temperature.

1. Toluene Flow Rate

   $= 2053 \text{ scfm waste gas} \times \frac{500}{10^6} = 1.027 \text{ scfm}$

2. Gross Heat for Toluene

   - From Table I, for toluene, gross heat

     = 4484 Btu/scf x 1.027 scfm

     = 4605 Btu/min

3. Available Heat from Toluene

   - Using Figure 4, at a flue gas temperature of 1400°F and at 0% excess air, available heat from toluene

     = 0.61 x Gross Heat

     = 0.61 x 4605 Btu/min

4. Credit for Preheat

   - From Table I, combustion air required

     = 42.88 scf air/scf toluene

   - Total combustion air

     = 1.027 x 42.88 scfm air

     = 44.04 scfm air

   - Credit for preheat

     $= 44.04 \text{ scf} \times 4.42 \frac{\text{Btu}}{\text{scfm}}$

     = 44.04 x 4.42 Btu/min

5. Total Available Heat From Toluene

= available heat + credit for preheat

= 0.61 x 4605 + 44.04 x 4.42 Btu/min

= 3003.7 Btu/min

6. Heat Balance: Heat Input = Heat Consumption

668 x G + 4.42 x 10.36 x G + 3003.7

= (2053 - 10.36 x G - 44.04) x 21.71

- Solving for G, G = 43.3 scfm natural gas

Comparing the two examples, it may be seen that the natural gas savings is 4.2 scfm, or 8.8% if the heat value of the solvent is considered.

Computations for Oil Requirements

To illustrate the effects of oil firing and the use of external combustion air on the calculations, the situation in Example 2 may be reworked for oil firing.

Example 3—Determine the quantity of #2 fuel oil (PS 100, Table IV) required to incinerate 3000 scfm of air conditioning 500 ppm of toluene, where the air temperature is 300°F. The oil burner is supplied with 120% theoretical air taken from outside the waste gas stream.

1. 120% theoretical air = 20% excess air

From Figure 4, the available heat at 1400°F and 20% excess air is approximately 55% of the gross heat value of fuel oil, which is 136,000 Btu/gal. from Table IV.

2. Heat Input

= the sum of the available heats of oil and toluene plus credit for preheat combustion air:

$$= 0.55 \times 136,000 \times Q + 3,003.7$$

$$+ 197.3 \ \frac{\text{ft}^3}{\text{lb}} \times 6.83 \ \frac{\text{lb}}{\text{gal}} \times 4.42 \ \frac{\text{Btu}}{\text{ft}^3} \times Q$$

where Q = quantity of oil burned, gallons/minute

$= 74{,}800 \times Q + 3{,}007 + 5{,}596 \times Q$

$= 80{,}756 \times Q + 3{,}003.7$ Btu/min

3. Heat Consumption is the waste gas flow less the air consumed in the combustion of toluene

   = (scfm waste gas - scfm required for combustion of toluene)

   x enthalpy difference (1400°F - 300°F)

   - Thus, heat consumption

     $= (2053 \text{ scfm} - 44.04 \text{ scfm}) \times 21.71 \frac{\text{Btu}}{\text{scf}}$

     $= 43{,}615$ Btu/min

4. Heat Balance: Heat Input = Heat Consumption

   - Thus

     $80{,}756\, Q + 3{,}003.7 = 43{,}615$

   - where

     $Q = 0.5$ gallons/minute

A comparison of gross heat inputs for Examples 2 and 3 shows:

gross heat input (Example 2) = 43.3 scfm x 1100 Btu/scf

= 47,630 Btu/min

gross heat input (Example 3) = 0.5 gal/min x 136,000 Btu/gal

= 68,000 Btu/min

Avoiding the use of outside air for fuel combustion (as in Example 2) results in a significant savings of heat input and thus of operating costs.

Combustion Chamber Size

The size of the combustion chamber will be determined by both the volumetric flow rate of the waste gas stream and combustion products at the design temperature and the design retention time. Since the combustion chamber should be considered as only that zone in which the design combustion temperature is attained, some burner types may necessitate a mixing zone before the combustion zone. Calculations follow for the combustion chamber volume.

Example 4—For the conditions in Example 2, find the combustion chamber volume required for combustion at 1400° F using natural gas fuel with internal combustion air; the desired retention time is 0.50 seconds.

1. From Example 2, waste gas required for the combustion of natural gas

   = 10.36 scf/scf x 43.3 scfm

   = 448.6 scfm

   Combustion products from natural gas (from Table III)

   = 11.453 scf/scf x 43.3 scfm

   = 495.9 scfm

2. From Example 2, waste gas required for the combustion of toluene

   = 42.88 scf/scf x 1.027 scfm

   = 44.04 scfm

   Combustion products from toluene (from Table I)

   = (7.0 + 3.0 + 33.88) scf/scf x 1.027 scfm

   = 46.09 scfm

3. Flow through the combustion chamber

   = (2053 - 448.6 - 44.04) + (495.9 + 46.09)

   = 2102 scfm

   $$= 2.02 \times \frac{460 + 1400}{460 + 60} \text{ acfm at } 1400^\circ\text{F}$$

   = 7520 acfm at 1400° F

4. Volume of combustion chamber needed for 0.5 second retention time

   $$= 7520 \text{ acfm} \times 0.5 \text{ second} \times \frac{1}{60} \frac{\text{min}}{\text{second}}$$

   = 62.67 cubic feet

Table II

Enthalpies of Gases Expressed in Btu/scf of Gas, Reference 60°F

°F	N_2	O_2	Air	H_2	CO	CO_2	H_2O[a]
60	-	-	-	-	-	-	-
77	0.31	0.31	0.32	0.31	0.32	0.39	0.36
100	0.74	0.74	0.74	0.73	0.74	0.94	0.85
200	2.58	2.61	2.58	2.55	2.58	3.39	2.98
300	4.42	4.50	4.42	4.40	4.43	5.98	5.14
400	6.27	6.43	6.29	6.24	6.29	8.69	7.33
500	8.14	8.40	8.17	8.09	8.18	11.52	9.52
600	10.02	10.40	10.07	9.89	10.08	14.44	11.81
700	11.93	12.43	12.00	11.77	12.01	17.45	14.11
800	13.85	14.49	13.95	13.61	13.96	20.54	16.45
900	15.80	16.59	15.92	15.47	15.94	23.70	18.84
1,000	17.77	18.71	17.92	17.36	17.94	26.92	21.27
1,100	19.78	20.85	19.94	19.20	19.97	30.21	23.74
1,200	21.79	23.02	21.98	21.08	22.02	33.55	26.26
1,300	23.84	25.20	24.05	22.95	24.10	36.93	28.82
1,400	25.90	27.40	26.13	24.87	26.19	40.36	31.42
1,500	27.98	29.62	28.24	26.80	28.31	43.85	34.08
1,600	30.10	31.85	30.38	28.70	30.44	47.35	36.77
1,700	32.21	34.10	32.50	30.62	32.58	50.89	39.49
1,800	34.34	36.34	34.66	32.52	34.74	54.48	42.26
1,900	36.48	38.61	36.82	34.45	36.93	58.07	45.06
2,000	38.65	40.90	38.99	36.43	39.12	61.71	47.91
2,100	40.84	43.17	41.18	38.49	41.31	65.35	50.78
2,200	43.00	45.47	43.39	40.57	43.53	69.02	53.68
2,300	45.24	47.79	45.61	42.66	45.74	72.71	56.64
2,400	47.46	50.11	47.83	44.71	47.99	76.43	59.59
2,500	49.67	52.43	50.07	46.82	50.23	80.15	62.60
3,000	60.91	64.18	61.39	57.22	61.55	98.96	77.98
3,500	72.31	76.13	72.87	68.14	73.00	118.15	93.92
4,000	83.79	88.29	84.42	79.38	84.56	137.62	110.28
4,500	95.37	100.64	96.11	90.68	96.21	157.20	126.96
5,000	107.04	113.20	107.91	102.42	107.93	176.93	143.92
5,500	118.78	125.89	119.78	114.21	119.70	196.77	161.07
6,000	132.54	139.74	131.73	126.16	131.52	216.77	178.41
6,500	142.37	151.72	143.76	138.35	143.37	236.88	195.82

[a] Enthalpies are for a gaseous system, and do not include latent heat of vaporization. L_v = 1,059.9 Btu/lb or 50.34 Btu/scf of H_2O vapor at 60°F and 14.696 psia.

Source: *Air Pollution Engineering Manual,* EPA AP-40, 2nd Ed., 1973.

Table III

Combustion Characteristics of Natural Gas

Average analysis, volume %[a]

CO_2	0
N_2	5.15
O_2	0
CH_4	81.11
C_2H_6	9.665
C_3H_8	3.505
$i\text{-}C_4H_{10}$	0.19
$n\text{-}C_4H_{10}$	0.24
C_5+	0.09
C_6+	0.05
	100.00

Average gross heat, 1,100 Btu/ft^3

Air required for combustion

Theoretical - 10.360 ft^3/ft^3 gas

20% excess air - 12.432 ft^3/ft^3 gas

Products of combustion/ft^3 of gas

	Theoretical air		20% excess air	
	Vol	Wt	Vol	Wt
CO_2	1.134 ft^3	0.132 lb	1.134 ft^3	0.132 lb
H_2O	2.083	0.099	2.083	0.099
N_2	8.236	0.609	9.873	0.731
O_2	-		0.435	0.037
Total	11.453 ft^3	0.840 lb	13.525 ft^3	0.999 lb

Available heat, Btu/ft^3 gas,[a] based on latent heat of vaporization of water at 60°F

Temp, °F	Available heat, Btu, with theoretical air	Available heat, Btu, 20% excess air
100	988.6	992.2
150	976.1	973.0
200	963.7	958.5
250	952.1	949.9
300	941.0	932.0
350	928.8	917.8
400	917.8	905.1
450	906.2	891.5
500	894.6	878.0
550	882.7	864.1
600	870.9	850.4
700	846.2	821.8
800	820.7	792.3
900	797.7	765.3
1,000	772.6	736.2
1,100	747.2	706.6
1,200	721.3	676.5
1,300	693.0	643.6
1,400	668.6	615.4
1,500	642.7	584.5
1,600	614.6	552.9
1,700	589.8	523.7
1,800	562.3	491.7
1,900	534.8	459.9
2,000	507.5	428.2
2,100	478.7	394.9
2,200	450.7	362.5
2,300	421.9	329.1
2,400	393.0	295.6
2,500	364.6	262.6
3,000	219.1	94.2
3,500	70.4	--

[a] Average of two samples analyzed by Southern Calif. Gas Co., 1956.

Source: *Air Pollution Engineering Manual,* EPA AP-40, 2nd Ed., 1973.

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Table IV

Combustion Data Based on 1 Pound of Fuel Oil[a,b]

Constituent		PS No. 100		PS No. 200		PS No. 300		PS No. 400	
Common Name		Kerosine/ Distillate		Straight-run fuel oil		Low-crack fuel oil		Heavy-crack fuel oil	
Density, lbs./gal.		6.83		7.50		8		8.33	
		ft^3	lb	ft^3	lb	ft^3	lb	ft^3	lb
Theoretical air (40% sat'd at 60°F)		197.3	15.04	185.1	14.11	179.1	13.66	177.2	13.51
Flue gas constituents with theoretical air	CO_2	26.73	3.104	27.08	3.144	27.61	3.207	27.86	3.236
	SO_2	0.002	0.004	0.142	0.0240	0.130	0.0220	0.142	0.0240
	N_2	154.8	11.44	145.2	10.74	140.5	10.39	139.0	10.28
	H_2O formed	28.76	1.368	22.75	1.082	19.18	0.9118	17.86	0.8491
	H_2O (fuel)	-	-	-	-	0.011	0.0005	0.011	0.0005
	H_2O (air)	1.367	0.0662	1.283	0.0621	1.242	0.0601	1.228	0,0595
	Total	211.659	15.9786	196.455	15.0521	188.673	14.5914	186.101	14.4491
Amount of flue gas with % excess air as indicated	0	211.7	15.98	196.5	15.05	188.7	14.59	186.0	14.45
	7.5	226.5	17.11	210.4	16.11	202.1	15.62	199.4	15.46
	10	231.4	17.48	215.0	16.46	206.6	15.96	203.8	15.80
	12.5	236.4	17.86	219.6	16.81	211.1	16.30	208.3	16.14
	15	241.3	18.24	224.3	17.17	215.6	16.64	212.7	16.48
	17.5	246.2	18.61	228.9	17.52	220.0	16.98	217.1	16.81
	20	251.2	18.99	233.5	17.87	224.5	17.32	221.5	17.15
	30	270.9	20.49	252.0	19.28	242.4	18.69	239.3	18.50
	40	290.6	22.00	270.5	20.69	260.3	20.05	257.0	19.85
	50	310.4	23.50	289.1	22.11	278.3	21.42	274.7	21.21
	75	359.7	27.26	335.3	25.63	323.0	24.84	319.0	24.58
	100	409.0	31.02	381.6	29.16	367.8	28.25	363.3	27.96
SO_2 % by vol. and wt. with theoretical air		0.0011	0.0025	0.072	0.16	0.069	0.15	0.076	0.17
Approximate Btu/gal.		136,000		142,000		146,000		152,000	

a. Combustion products calculated for combustion with air 40% saturated at 60°F. All volumes measured as gases at 60°F. Moisture in fuel included where indicated.

b. Maximum accuracy of calculations: 1:1,000.

Source: *Air Pollution Engineering Manual*, EPA AP-40, 2nd Ed., 1973.

Burner Types

A great deal of ingenuity has gone into the design of commercial afterburners. Experience shows that economic and performance advantages accrue to systems that incorporate uniform and short flame zones, maximum contact between the fumes and the flame, and intensive mixing. Beyond the initial combustion and mixing zone, the design features are less critical, so that simple cylindrical or rectalinear sections tend to be used. Cooling may have to be provided beyond the combustion zone to protect the blower and stack. This may be accomplished by heat recovery or by the introduction of outside air.

There are two types of burner designs, based on arrangement: distributive and discrete.

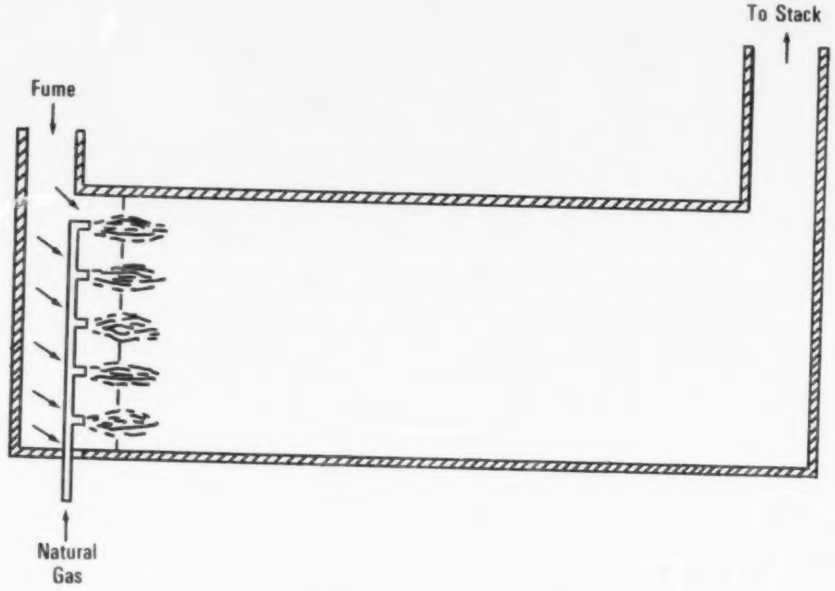
Natural gas and propane have commonly been used for afterburners, since gaseous fuels are adaptable to uniform and short combustion zones. Distributive burners, shown in Figure 5A, allow the use of the waste gas stream for combustion air and are compact and efficient.

The line-type burner, shown in Figure 5B, uses a gas manifold or multiport construction which injects gas into a network of divergent openings from a metal plate. The waste gas enters through perforations in the sidewalls of the plate and is mixed with the gas by the jet action, forming a short flame zone beyond the plate. Flame contact is extended by this design. The metal plate must be highly temperature resistant to avoid damage, and the amount of preheat is limited to approximately 1000°F for the same reason.

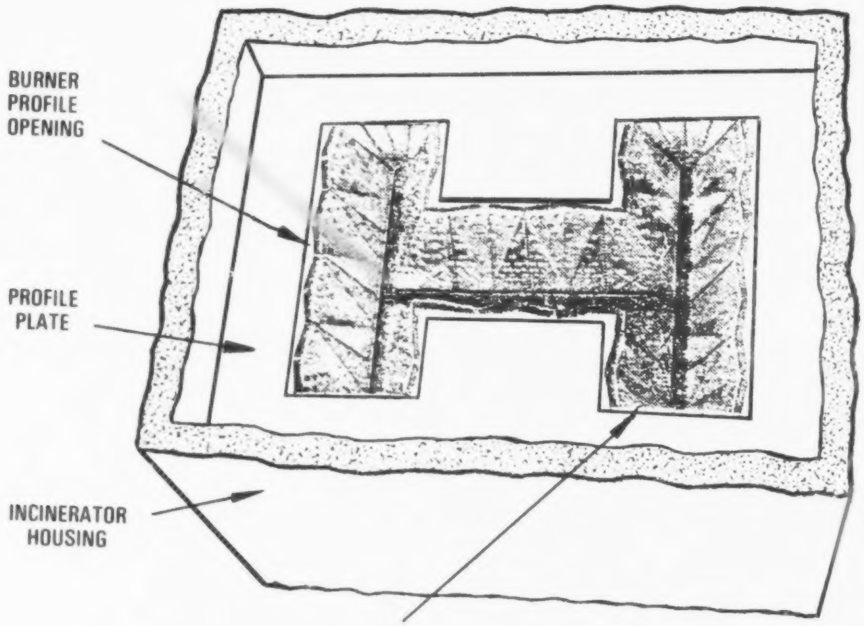
A variant of the same general type, the multijet burner, is shown in Figure 6. It differs in that a ceramic burner grid may be used. Gas and air enter the conical mixing and combustion zone from the upstream face. This type of construction is less subject to heat damage, but part of the waste gas stream must be bypassed if a stable flame is to be obtained. Flame contact is lost with the portion of fume bypassed, and the combustion chamber must be extended to allow for mixing of the gases beyond the flame. Figure 6 shows baffles used to provide mixing.

Where oil is burned, or only interruptible gas is available, a single premix burner is commonly used. The air supplied to the burner may be outside air, or if the waste gas stream is reasonably clean it may be withdrawn from the ducting upstream. An arrangement of this type is shown in Figure 7. Since flame contact in this type of system is relatively poor, some arrangement is needed to obtain rapid mixing of the flame with the waste gas. Baffles may be used for this purpose, or turning vanes in the air inlet zone. Occasionally, a tangential inlet for the gas stream is provided in a cylindrical combustion chamber. The artificially induced swirl provides mixing throughout the combustion zone.

Afterburners have been constructed in both horizontal and vertical configurations. The horizontal type is more compatible with heat recovery systems, while the vertical type (under forced draft) can reduce the cost of the stack.


To Stack
Fume
Natural Gas

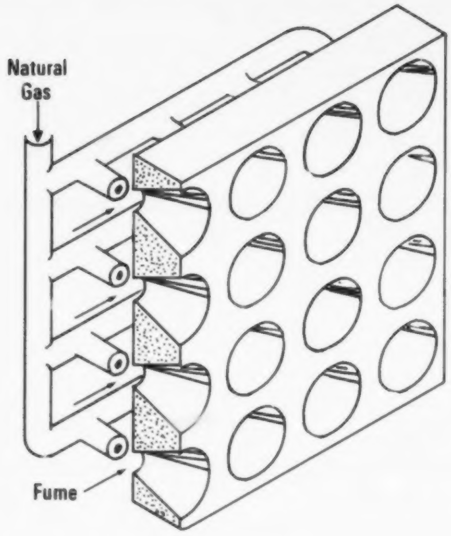
A. Afterburner with Distributed Burner


BURNER PROFILE OPENING
PROFILE PLATE
INCINERATOR HOUSING
COMBUSTIFUME BURNER

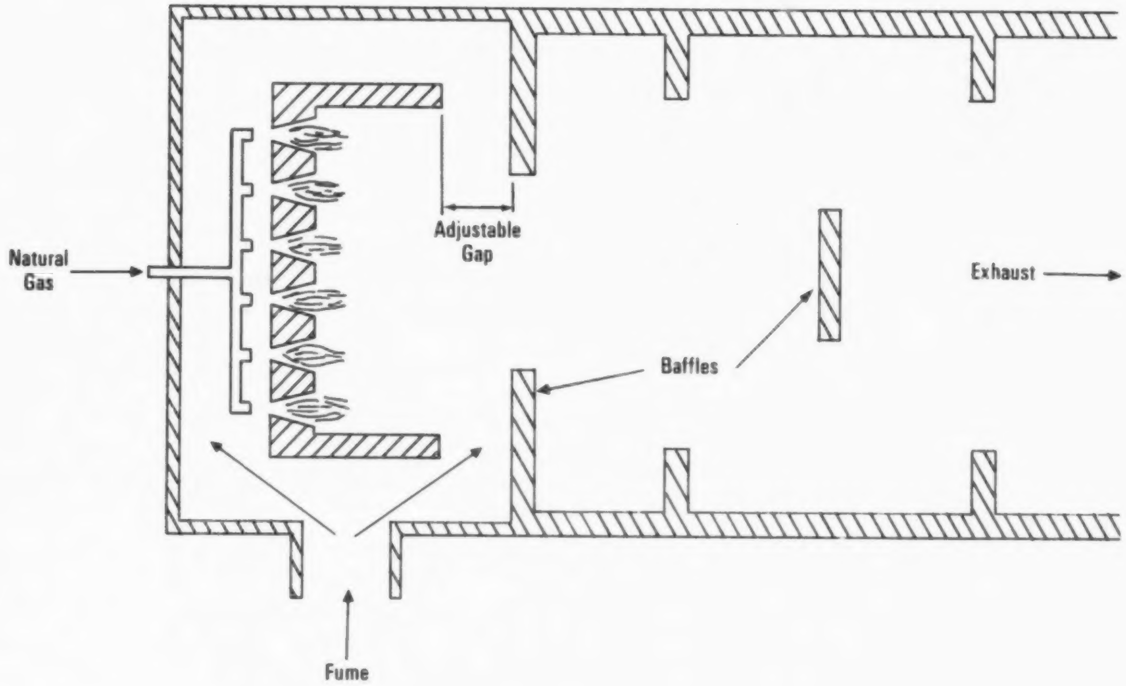
B. Maxon Combustifume Burner

Source: *Afterburner Systems Study*, Shell Development Company, 1972.

Figure 5. Maxon Combustible Burner


Natural
Gas
Fume

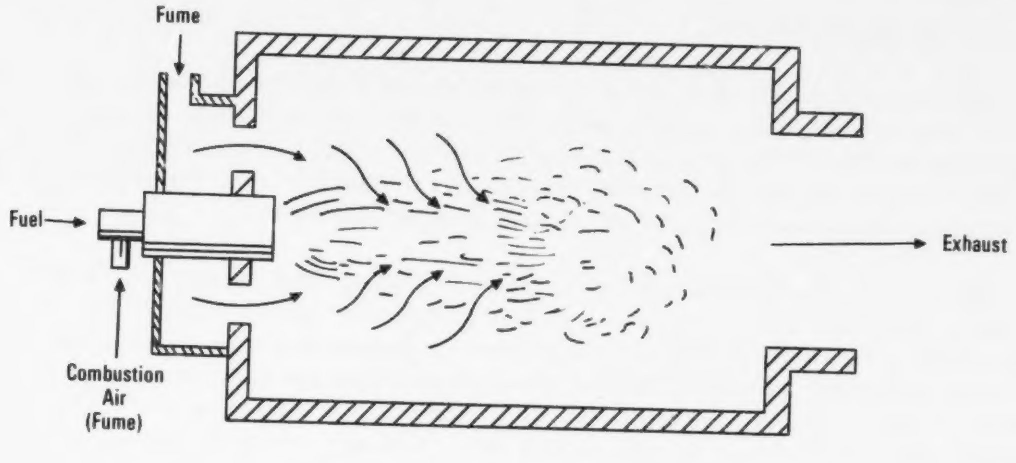
A. Hirt Multijet Gas Burner


Natural
Gas
Adjustable
Gap
Exhaust
Baffles
Fume

B. Afterburner System Employing Multijet Burner

Source: *Afterburner Systems Study*, Shell Development Company, 1972.

Figure 6. Hirt Multijet Gas Burner



Source: *Afterburner Systems Study,* Shell Development Company, 1972

Figure 7. Afterburner Using a Discrete Burner

Accessories and Controls

Direct-flame incinerators will require thermocouple temperature sensors, used to monitor:

- Inlet waste gas temperature. If the waste gas is preheated, a preheat bypass control is sometimes used to prevent the temperature from going above safe maximum inlet values.
- Temperature in the combustion area. Temperatures much in excess of the required minimum result in higher fuel and maintenance costs; for this reason, the fuel injection rate is controlled through a burner control that incorporates a sensor.
- Temperatures downstream from the combustion area, especially if heat recovery is a part of the system.

In addition, sensors and controls are frequently provided to monitor or control pressure drops across the incinerator and combustion fires. The safeguards used against combustion fires include flame detectors, automatic shutdown provision in case of flame-out, and pressure switches. These devices are based on approval by safety and fire protection organizations such as the Underwriters Laboratory, Inc., the Factory Mutual System, the Factory Insurance Association, and the National Fire Protection Association.

CATALYTIC INCINERATION

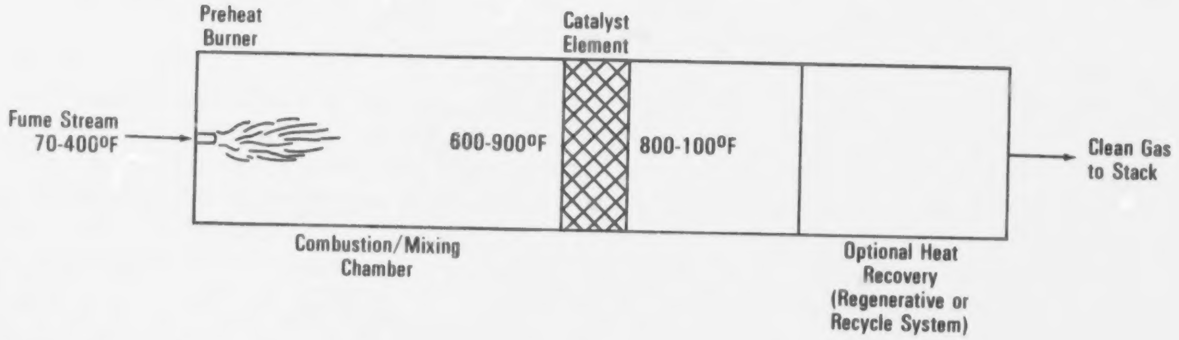
The catalytic incinerator differs from the direct-fired unit in that an active catalyst is used to reduce the ignition temperature of the solvent in the waste gas stream. Since less heating of the incoming gases is required, fuel consumption is reduced. Further benefits include the smaller combustion chamber and the reduced equipment maintenance associated with the lower operating temperatures.

Structurally, a catalytic incinerator differs from a direct-fired unit in that a burner system in a preheat chamber is used to raise the temperature of the incoming gases to 600°F - 900°F. The hot gases are then passed through a catalyst bed where the fume is burned, releasing further heat and elevating the gas temperature to 800°F - 1100°F. Since no flame contact is involved, the preheat section is frequently a discrete burner followed by a simple mixing zone, although a distributive burner may also be used. Little or no combustion occurs beyond the burner, so the residence time at peak temperature can be quite short. The net result is a somewhat smaller physical system than the direct-fired unit. Figure 8 is a diagram of a typical catalytic incinerator.

Gas Conditioning

The catalysts used in catalytic incineration, normally platinum or palladium, are extremely sensitive to contamination and catalyst failures are common. Heavy metals such as mercury, arsenic, lead, and zinc will inactivate the catalytic surface. Plastic resins and tarlike materials may coat the catalyst, as may otherwise-inert materials such as dusts and metallic oxides. As a result, the incoming waste gas stream must be completely free of materials of this type. Where doubt exists as to the contaminants in the gas stream, it is wise to use thermal incineration.

Where the advantages of catalytic incineration appear to warrant the expense of precleaning gases, fabric filters or electrostatic precipitators may be used for dust and scrubbers may be used for either particles or heavy liquid droplets. Water vapor



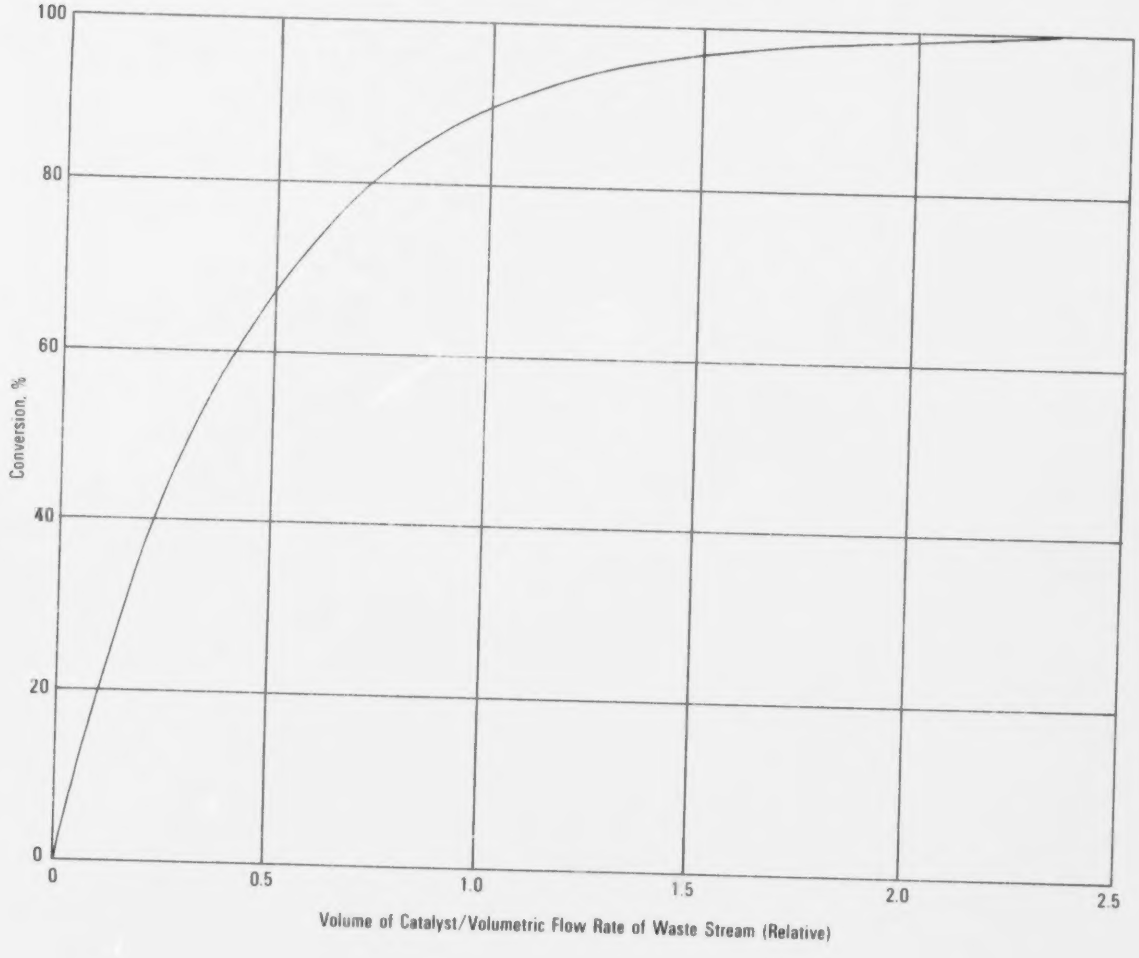
Source: *Afterburner Systems Study,* Shell Development Company, 1972.

Figure 8. Schematic of Catalytic Afterburner System

will not affect the incinerator, although the temperature loss associated with water scrubbing will increase fuel requirements.

Catalytic Combustion

The degree of solvent vapor oxidation that can be expected on a catalyst is affected by the vapor composition, the reaction temperature, the surface area of the catalyst, and the degree of contact between the solvent and catalyst. The last two variables will depend on the commercial design of the catalyst and its support structures. A generalized curve showing the relative effect of catalyst volume/flow ratio on combustion efficiency is given in Figure 9. It is normal practice to follow the manufacturer's recommendation concerning catalyst volume for a given application, since much of the applications technology is based on field experience.

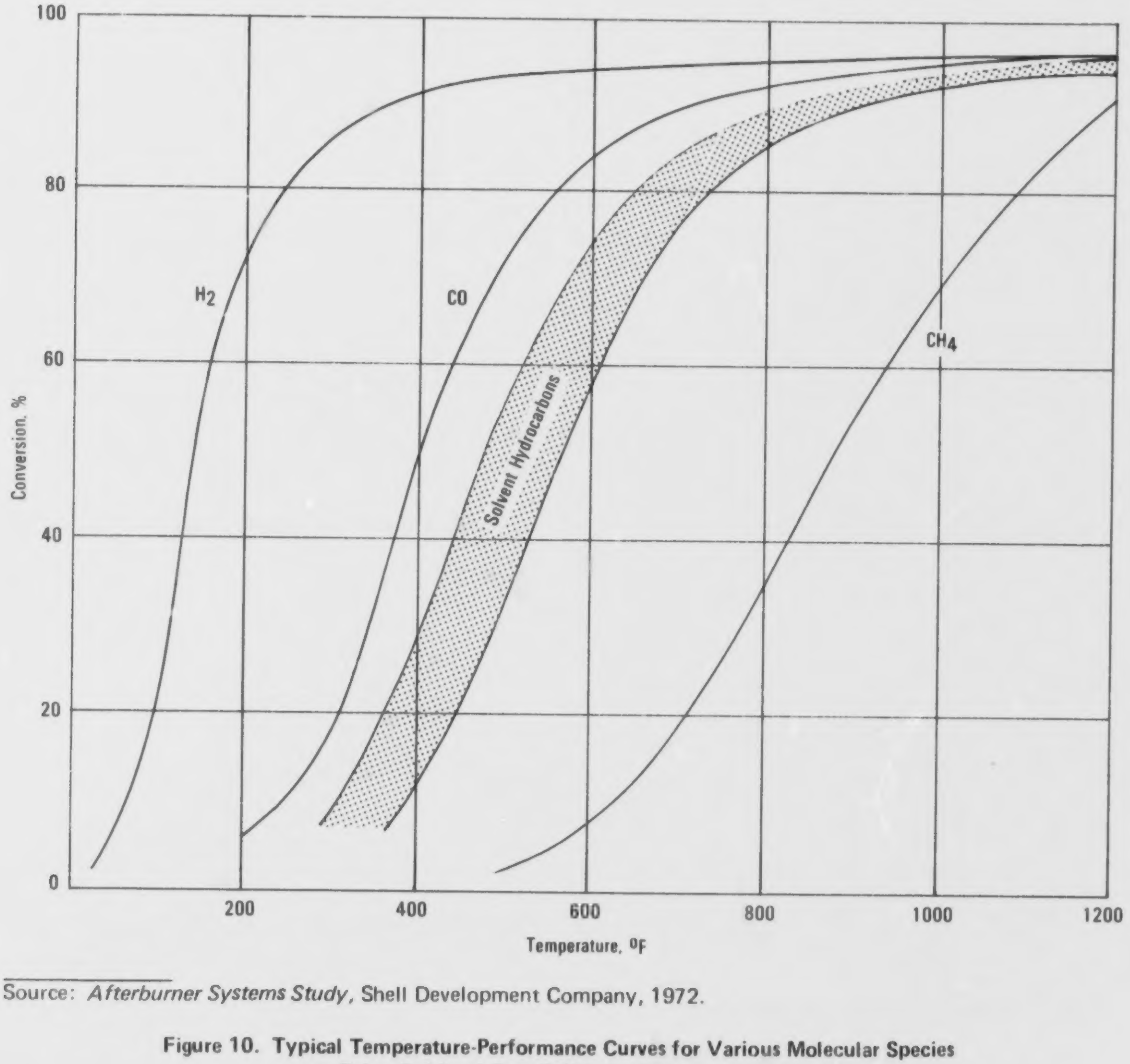


Source: *Afterburner Systems Study,* Shell Development Company, 1972.

Figure 9. Combustion Efficiency as a Function of Catalyst-Volume/Flow Ratio

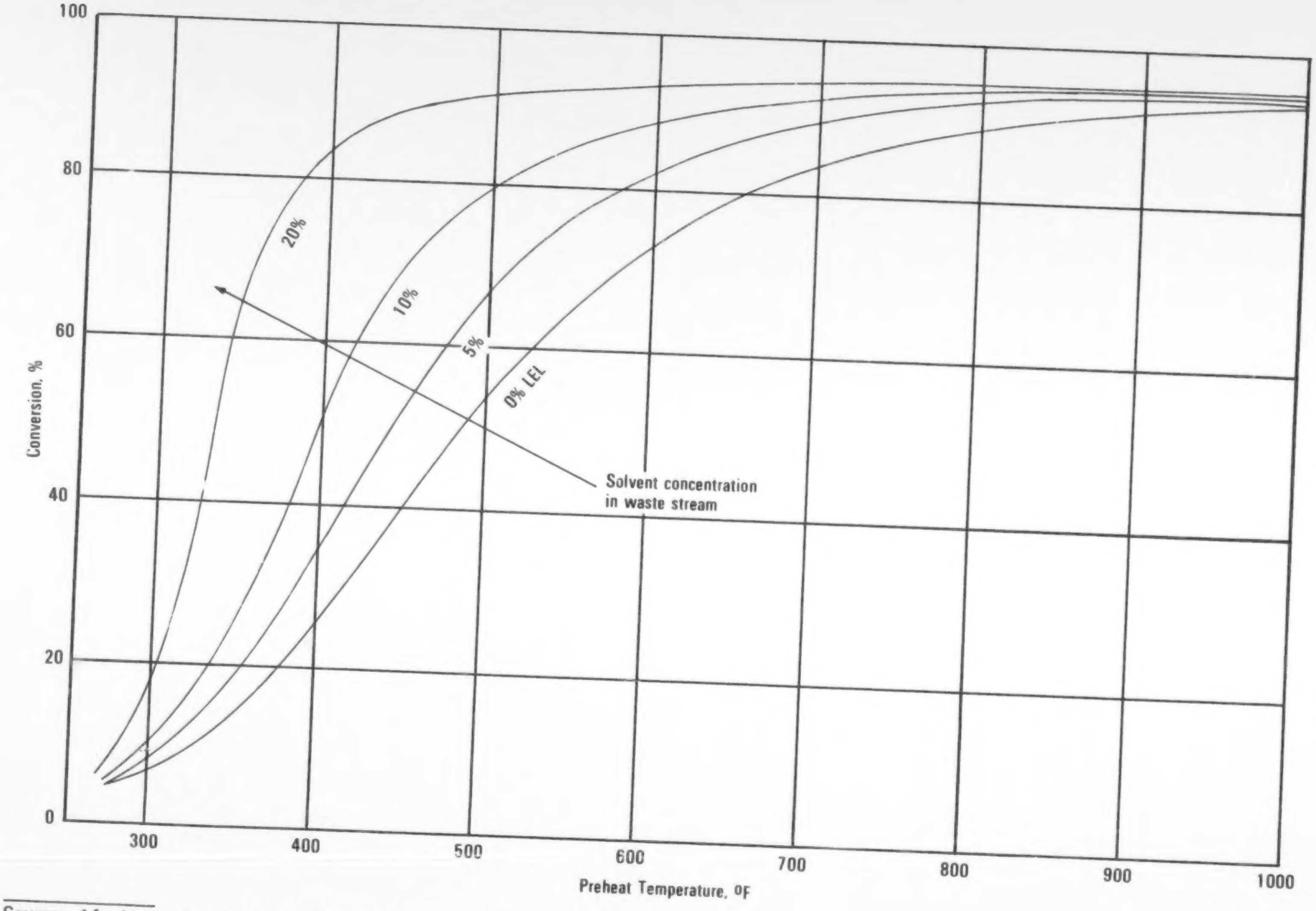
Both the solvent used and its concentration influence the design preheat temperature for the catalyst. Figure 10 shows catalyst temperatures required for combustion of typical solvent hydrocarbons with some of the common combustible gases. These temperatures must be modified to reflect the concentration of solvent. As may be seen from Figure 11, lower vapor concentrations are considerably more difficult to oxidize because of chemical kinetics and the lack of additional heat gain from the catalyst.

Commercial catalysts consist of small quantities of platinum or platinum/palladium alloys deposited on metallic or ceramic support structures. One manufacturer electroplates the active metal onto the surface of fine nichrome ribbon that has been geometrically packed to obtain a high surface area and void ratio. The nichrome structure is quite inert and will withstand temperatures up to 1500°F without damage. Several



Source: *Afterburner Systems Study*, Shell Development Company, 1972.

Figure 10. Typical Temperature-Performance Curves for Various Molecular Species Being Oxidized Over Pt/Al_2O_3 Catalysts



Source: *Afterburner Systems Study*, Shell Development Company, 1972.

Figure 11. Effect of Solvent Concentration on Required Preheat Temperature

other manufacturers use a ceramic base coated with a porous wash coat of aluminum oxide. The catalyst is deposited on or in the porous surface coat in the form of small crystals. The base structure may be pelletized or, more commonly, formed into a honeycomb structure. The aluminum-oxide-based form provides somewhat greater catalyst activity than the all-metal form.

Process Design Principles

For catalytic incinerator process design, it will be necessary to determine the degree of preheat required for the solvent fume, emission concentration, and the efficiency desired. The subsequent heat and volume calculations are similar to those for thermal incinerators, except that the heat is released in two stages. The cross-sectional area of catalyst required is based on manufacturers' recommended face velocities, which range from about 5 to 35 feet per second. A typical calculation of the fuel requirements and temperature profile follows:

Example 5—Given: A waste gas stream of 4500 acfm at 200°F contains 300 ppm of hexane. The gas stream is to be catalytically incinerated with a desired efficiency of 90%. Natural gas is available as a fuel.

Find: The preheat fuel required, and the temperature and rate of gas flow at the exit of the catalyst.

1. Since natural gas is available, a distributive preheat burner will be used to avoid the introduction of outside air.

2. From Figure 10, it may be seen that a catalyst temperature of approximately 900°F should be sufficient. Figure 11 confirms this temperature, at hexane concentrations of less than 10% LEL. Since the temperature rise over the catalyst will be small with only 300 ppm of hexane, the conservative assumption of 900°F preheat temperature will be used to size the burner. The natural gas flow will actually be slightly less than the calculated value.

3. Waste gas flow in scfm

$$= 4500 \times \frac{460 + 60}{460 + 200}$$

$$= 3545 \text{ scfm}$$

4. Heat Input (neglecting contribution from hexane)

= (Available heat at 900°F, 0% excess air) x G

+ credit for initial heat of combustion air to 200°F

where G = scfm natural gas required

- From Table III, available heat at 900°F

  = 797.7 Btu/scf

- Credit for initial heat

  $= G \times 10.36 \ \frac{\text{scf air}}{\text{scf gas}} \times$ enthalpy difference (200° - 60°)

- From Table II, enthalpy difference (200° - 60°)

  = 2.58 Btu/scf air

- Thus, heat input

  $= 797.7 \times G + G \times 10.36 \times 2.58$

  $= 824.4 \times G$ Btu/min

5. Heat Consumption

   = (scfm waste gas - scfm needed for combustion) x enthalpy change (900°F - 200°F)

   - From Table II, enthalpy difference (900°F - 200°F)

     = 2.58

   - Thus, heat consumption

     $= (3545 - 10.36 \times G)(15.92 - 2.58)$ (from Table II)

     $= 47290 - 138.2 \times G$

6. Heat Balance: Heat Input = Heat Consumption

   - Thus, $824.4\ G = 47290 - 138.2\ G$

   - Solving for G, $G = 49.1$ scfm natural gas

7. The combustion gas at this point will consist of:

   (i) air $= 3545 - 10.36 \times 49.1 = 3036$ scfm

   From Table III, products of natural gas combustion

   (ii) $CO_2 = 1.134$ scf/gas $\times 49.1 = 55.7$ scfm

(iii) H_2O = 2.083 scf/scf gas x 49.1 = 102.3 scfm

(iv) N_2 = 8.236 scf/scf gas x 49.1 = 404.4 scfm

8. Heat available from hexane burning over catalyst

- Hexane flow rate = $3545 \times \frac{300}{10^6}$ = 1.064 scfm

- From Figure 4, at 900°F and 0% excess air, approximately 72% of gross heat from hexane is available. Gross heat value for hexane is 4762 Btu/scf (from Table I)

- Heat available from hexane

  = 0.72 x 4762 x 1.064 Btu/min

  = 3648 Btu/min

9. Combustion air required to burn hexane (from Table I)

   = 45.26 scf air/scf hexane x 1.064 scf

   = 48.2 scfm

   Products of hexane combustion (from Table I)

   CO_2 = 6.0 x 1.064 = 6.4 scfm

   H_2O = 7.0 x 1.064 = 7.5 scfm

   N_2 = 35.76 x 1.064 = 38.0 scfm

10. Combustion gases after the catalyst will consist of (from steps 7 and 9):

    (i) air = 3036 - 48.2 = 2987.8 scfm

    (ii) CO_2 = 55.7 + 6.4 = 62.1 scfm

    (iii) H_2O = 102.3 + 7.5 = 109.8 scfm

    (iv) N_2 = 404.4 + 38.0 = 442.4 scfm

11. Temperature at the end of the catalyst zone can be calculated by equating heat available from hexane (step 8) to the heat consumed in temperature increase in the combustion gases from step 10.

    - Assuming a linear enthalpy change between 900°F and 1000°F for air, CO_2, H_2O, and N_2, the heat consumed by combustion bases (from Table II)

$$= 2\ \frac{\text{Btu/scf}}{100°\text{F}} \times 2987.8 \text{ scfm air at } \Delta T$$

$$+ 3.22\ \frac{\text{Btu/scf}}{100°\text{F}} \times 62.1 \text{ scfm } CO_2 \times \Delta T$$

$$+ 2.43\ \frac{\text{Btu/scf}}{100°\text{F}} \times 109.8 \text{ scfm } H_2O \times \Delta T$$

$$+ 1.97\ \frac{\text{Btu/scf}}{100°\text{F}} \times 442.4 \text{ scfm } N_2 \times \Delta T$$

$= 73.14 \times \Delta T$ Btu/min

- Equating this to heat available from combustion of hexane (step 8)

$73.14 \times \Delta T = 3648$

$T = 50°F$

- Thus the final gas temperature

$= 900 + \Delta T$

$= 950°F$

12. The final flow rate, from step 10

$= 2987.8 + 62.1 + 109.8 + 442.4$

$= 3602$ scfm

$$= 3602 \times \frac{460 + 950}{460 + 60} \text{ acfm at } 950°\text{F}$$

$= 9767$ acfm at 950°F

These are typical calculations for sizing a catalytic afterburner.

Accessories and Controls

The accessories and controls for a catalytic incinerator are similar to those required for a direct-fired unit and include a temperature-regulated preheat burner system and a flame sensor for emergency shutdown. The burner control may be activated by the post-catalyst temperature to smooth out fluctuations in final temperature due to solvent variations.

Catalysts tend to become less effective with time, even with a clean waste-gas stream. The normal life will vary from a few months to 2 or 3 years, depending on the nature of the waste load. As the incinerator becomes less efficient, operating temperatures must be increased to offset the decreasing catalyst activity. Frequent or continuous effluent monitoring for hydrocarbons or carbon monoxide is the only way to be sure that emission regulations are being met unless the unit is operated at excessive temperatures. However, continuous monitoring is expensive, as is overheating.

PROCESS BOILERS

The use of boilers—existing or planned—for fume combustion may enable significant reductions in both capital and operating costs. The initial saving of the cost of a fume incinerator will be somewhat offset by the cost of boiler modifications and ducting. However, if the distance between the fume source and the boiler is not great, long-term savings can be substantial. An important factor is circumventing the cost of additional fuel for air pollution control only. In incineration, fuel is the major cost; further, the lighter grades used (gas or distillate oil) may be difficult to obtain.

There are a number of conditions that must be met for a boiler to function satisfactorily for fume incineration:

- The fume should be almost completely combustible. If not, the solids present will either foul the heat exchange surfaces or cause the boiler emissions to exceed applicable particulate emission regulations. If there are significant quantities of solids in the waste gas, the costs of increased maintenance of the boiler and/or control of the particulates may well exceed the purchase price of a fume incinerator.
- The contaminated gas stream should, preferably, constitute only a small fraction of the air requirements of the boiler. If the volume of the gas stream is large, special attention must be paid to the oxygen balance, mixing, and continuation of the air flow when the fume-emitting process is shut down.
- The oxygen concentration of the contaminated gas stream should be close to that of air to avoid incomplete combustion, which can produce tars that coat heat exchanger surfaces.
- The boiler must operate at all times when fume incineration is required.
- The fumes must be free of compounds, such as halogenated hydrocarbons, that accelerate corrosion of the boiler.

In addition:

- Baffling may be required in the combustion chamber to ensure adequate mixing and combustion of the fumes without bypassing.
- If the boiler-firing rate varies greatly, it may be worthwhile to install a small auxiliary boiler that will operate under steady load conditions to produce a base quantity of steam and serve as a fume incinerator.

Before a process boiler is used for fume incineration, a careful analysis should be made of the operations involved. In a new facility, it is generally possible to plan the layout and characteristics of individual boiler units to ensure that they will be economical and effective. In existing facilities some problems are inevitable, and an objective analysis is necessary to make certain that projected economies are realistic.

VAPOR ADSORPTION

Although adsorption of organic vapors is a proven technique for their control, its use in the metal coating industry for solvent vapor control is not common, for the following reasons:

- The low concentrations of solvent vapors in gas streams from metal coating operations make this technique very expensive.
- Flow rates associated with metal coating are large and the large adsorption units necessary for vapor removal are not cost-effective.
- Vapors from metal coating operations contain mixtures of solvents, and the solvents used frequently change, depending on coating needs. This makes solvent recovery by adsorbers impractical because of high costs of solvent separation, unless the solvent mixture can be used elsewhere as a secondary fuel.
- Process gas must be cooled to less than 100°F for adsorption, requiring additional cooling equipment.
- Adsorption beds are extremely susceptible to fouling from particulate matter in the process gas. The effective life of the adsorption medium can thus be prohibitively low.
- Under certain circumstances, low-temperature adsorption systems may require corrosion-resistant construction materials, increasing the initial outlay.

CHAPTER II

HEAT RECOVERY

Since fume incineration involves heating significant flows of air to temperatures as high as 1500°F, the potential for heat recovery is obvious. For large flows in thermal incinerators, heat recovery is nearly always economically justified. Catalytic incinerators operating at lower temperatures offer less opportunity for heat recovery, as do small incinerators where the increased capital requirement may exceed the value of the heat recovered over a reasonable period of time.

Heat may be recovered and reused in a number of ways. The most common is preheating the incoming contaminated gas stream to directly reduce the fuel needed for the desired operating temperature in the incinerator (primary heat recovery). Where the fume source is an oven, part of the incinerator exhaust gas may be used to heat the oven, either directly or indirectly. Heat may also be recovered as either hot air or steam for use in plant operations unrelated to the fume source (secondary heat recovery).

The choice of whether to use heat recovery, and in what form, depends on a number of process and economic factors. These are summarized in Table V. In this table, "effectiveness ratio" is the percentage of actual heat recovery relative to that theoretically obtainable.

Primary heat recovery for reducing fuel required for incineration is almost universally accomplished by using either cross-flow tubular or regenerative heat exchangers. The tubular type provides relatively low-cost cross-flow configurations for the low-pressure differentials encountered in incineration processes. Single- and double-stage units are illustrated in Figure 12. Since the cost is almost directly proportional to the number of stages, tubular exchangers are most commonly used in single-stage applications, where 40-50 percent heat recovery is considered adequate. The units are sensitive to fouling of the tube surfaces and are difficult to clean because of the complex arrangement of tubes. They should, therefore, be avoided where soot, tars, or possible polymerization products are present in the stack gases.

For high-efficiency heat recovery, regeneration by rotary heat exchangers is most commonly used. An example of this type is shown in Figure 13. A wheel with large surface area and sufficient bulk for a large heat capacity is rotated between the hot and cold gas streams. Heat is captured by the portions of the wheel exposed to the hot gases and lost as the wheel is rotated into the cool gas stream. Since the wheel is constantly exposed to heating and cooling, warping and thermal stress are potential problems in metal wheels and sophisticated construction is needed to overcome them. In recent years, however, ceramic materials with low thermal expansion (and freedom from corrosion) have been successfully used for the wheels.

Table V

Comparison of Heat Recovery Techniques

Type	Effectiveness Ratio, E	Additional Auxiliary Equipment	Limitations and Problems	Common Use
Tubular exchanger gas/gas	1 sta-50% max 2 sta-62% max 3 sta-85% max		1. May be easily fouled; frequent cleaning and maintenance. 2. Failures, differential thermal expansion. 3. Hot surfaces may crack or polymerize fume components, lay combustible deposit, initiate a fire. 4. Bulky, heavy, added roof load and/or floor space. 5. Corrosion if cools below dew point of flue gas.	Primary, secondary heat recovery
Regenerative (rotary) exchanger	up to 85%		1. Easily fouled. Use only on relatively clean streams. 2. Burnout if failure on rotary drive motor. 3. Requires attention to pressure balance to control leakage at seals. 4. Avoid cooling flue gas to dew point, but otherwise is relatively insensitive to corrosion. 5. Ignition if overheat fuel-rich stream.	Secondary heat recovery, to heat air entering oven

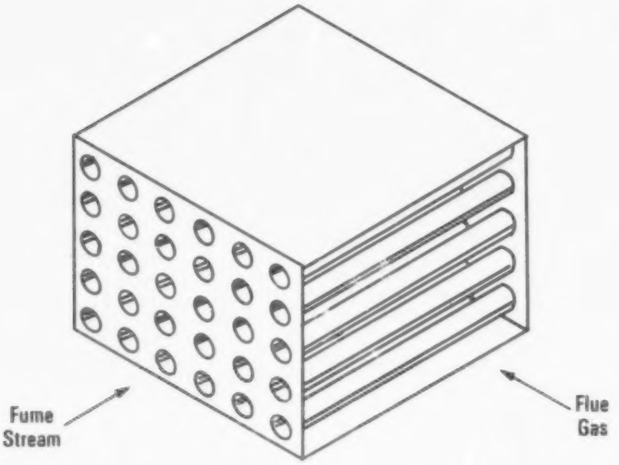
Table V (continued)

Type	Effectiveness Ratio, E	Additional Auxiliary Equipment	Limitations and Problems	Common Use
Flue gas recycle to oven	30%	Safety Controls	1. Process must be compatible with flue gas (condensation? sulfur in fuel? CO or CO_2? reduced oxygen? unburned fuel?) 2. Usefulness depends on temperature and heat requirements of fume generating process.	
Steam, generators, boilers, water heaters	to 75%	Extra burners and controls; safety controls Extra ducting, blowers controls	1. Ties steam generation to fume process and vice versa. 2. Match steam heating load to afterburning heat release. 3. Dew point and condensation on cold-water coils.	Secondary heat recovery
Heat pipe	to 60%		1. Can only be used for hot side temperature up to 800°F	To preheat oven air, secondary heat recovery

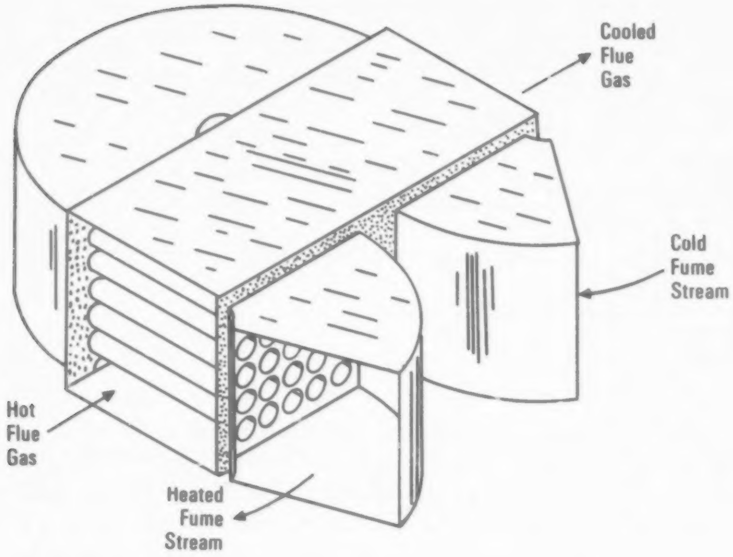
Adapted from: *Afterburner Systems Study*, Shell Development Company, 1972.

Rotary heat exchangers are capable of very high efficiency and offer significant cost and space savings over other high-performance heat exchangers. Fouling can be a problem if stick materials are handled, but inert dusts are tolerated at reasonable concentration. Cleaning is easier than with tubular-type exchangers.

The principal operating problem with rotary exchangers has been leakage from the seals separating the hot and cold gas streams. Since these seals must tolerate motion while subjected to temperature extremes, finding a substance and a design that would give reasonable life expectancy was technically difficult. However, in recent years manufacturers have managed to overcome this problem, at least for relatively clean gas streams.


Fume Stream
Flue Gas

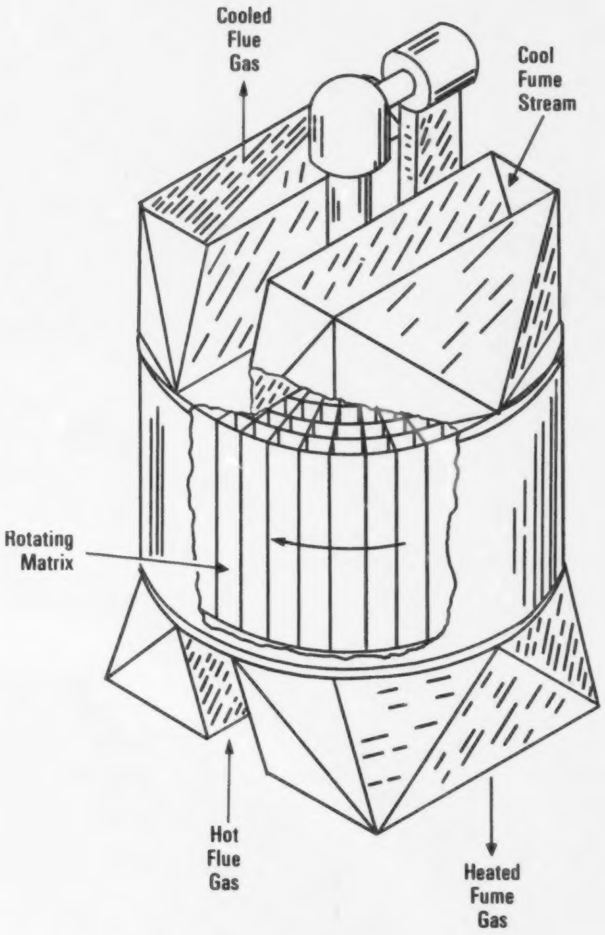
A. Shell and Tube Type Exchanger Cross-Flow Type


Cooled Flue Gas
Cold Fume Stream
Hot Flue Gas
Heated Fume Stream

B. 2-Pass, Cross-Flow Exchangers (Arranged to Place Units Counter-Flow)

Source: *Afterburner Systems Study*, Shell Development Company, 1972.

Figure 12. Typical Shell and Tube Heat Exchangers



Source: *Afterburner Systems Study,* Shell Development Company, 1972.

Figure 13. Rotary Regenerative Heat Exchanger

A heat recovery technique known as heat pipe is also commonly used. Here a refrigerant inside a series of tubes circulates between the hot and cold sides (Figure 14). As the liquid refrigerant enters the hot side of a tube, it absorbs heat from the hot gases and evaporates. The evaporated refrigerant then gives up its heat to the cold air stream and condenses. In this way, heat can be transferred from hot gases to cold air. Heat pipes are used for secondary heat recovery purposes like comfort heating. A limitation of the heat pipe technique is that the maximum hot-side temperature cannot be much in excess of 800°F. For this reason, the technique is used in conjunction with ovens on coating lines that have water-based or powder-deposition paint technologies, where incineration of the oven exhaust is not required.

In cases where additional process steam or heat is required in a plant, it may be more economical to let the fume incinerator serve the dual function of controlling air

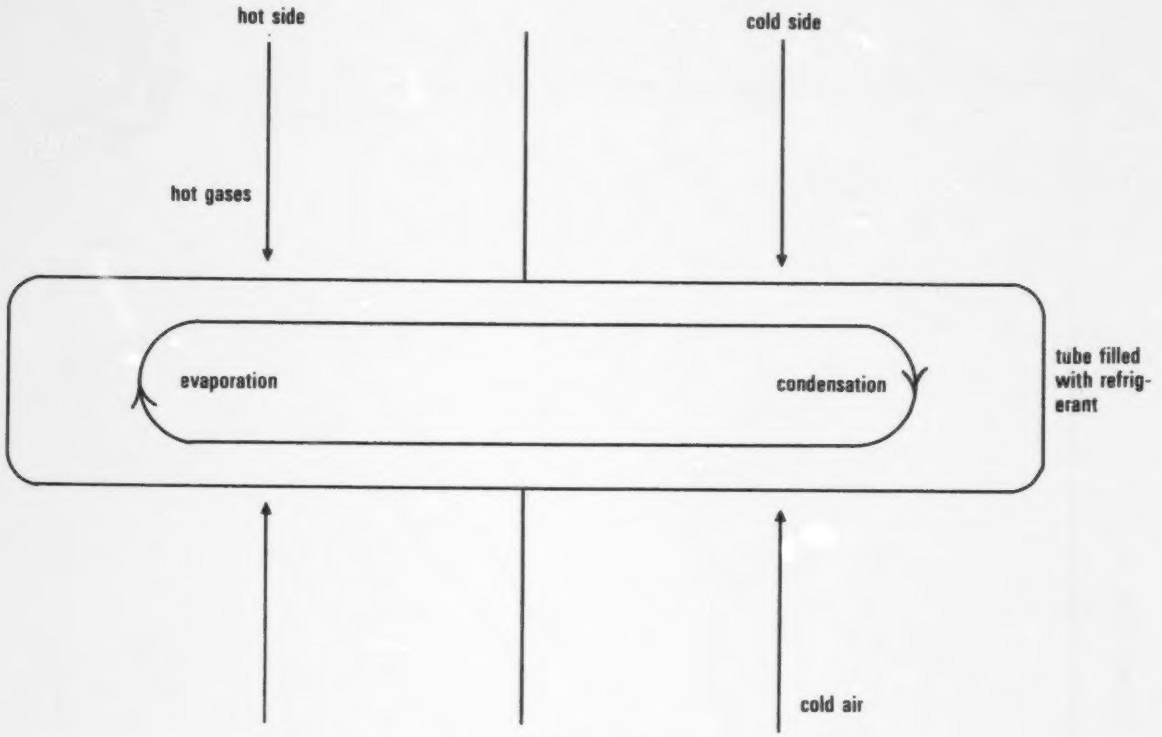
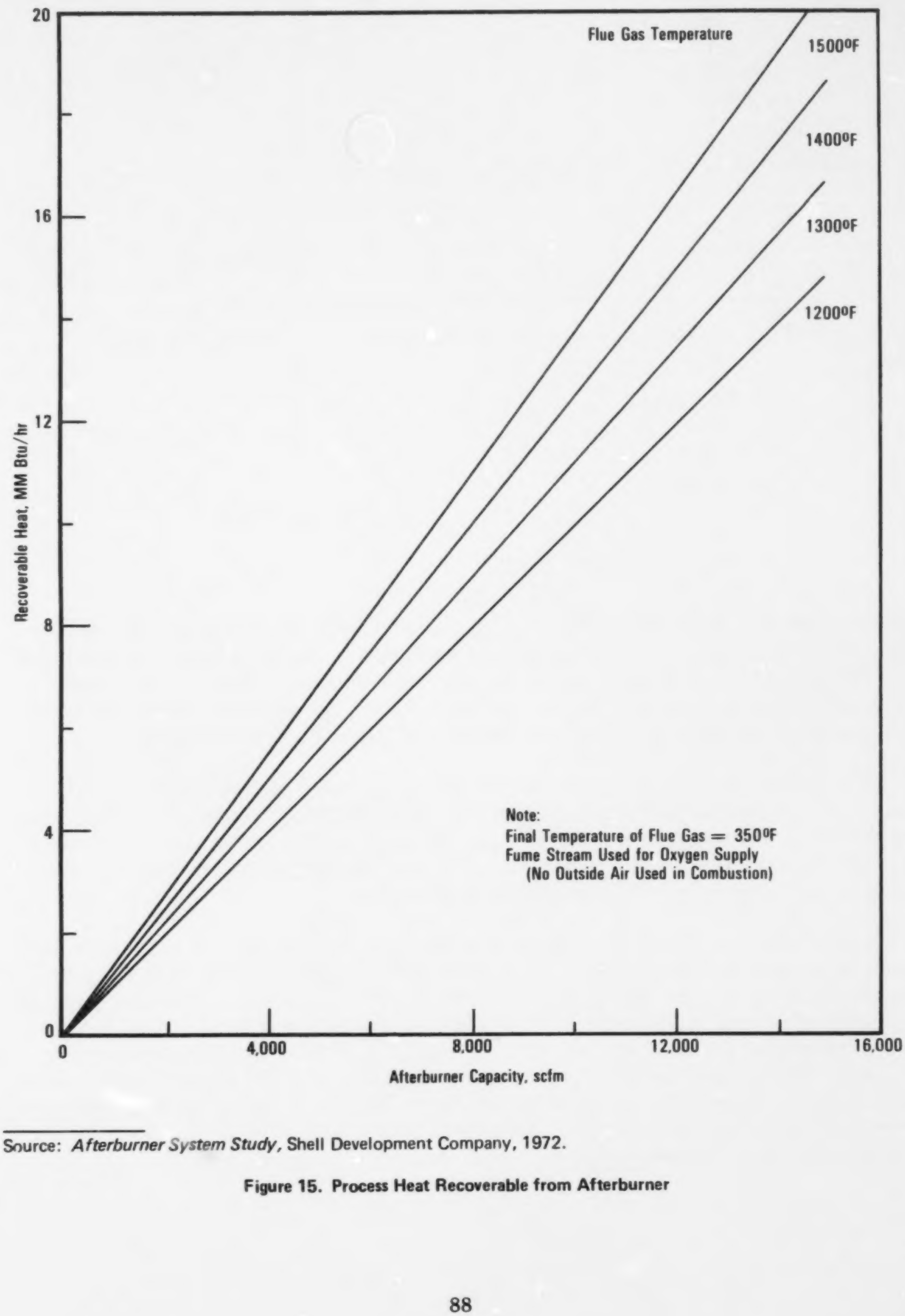


Figure 14. Heat Pipe

pollution and providing process heat. If separate boilers are constructed for process heat and for heat recovery to reduce fuel consumption in the incinerator, the total cost will be higher than for a single burner and heat recovery unit. For true economy, plant operations must be such that incineration of waste gases would not be necessary at times when the heat recovered from them could not be used in processes.

The process heat or steam available from afterburners of even moderate capacity can be substantial, as is shown in Figure 15. Recovery may be accomplished by burning the contaminated gas stream in a boiler, by using an afterburner followed by only the heat exchange portion of a boiler, or by using a conventional gas-liquid heat exchanger to produce a hot-fluid stream for process use.

Where the fume source is an oven, it is common to circulate part of the exhaust gases from the afterburner back to the oven to provide either part or all of the heat requirement. Care must be taken to prevent the exhaust gases from harming the product being processed in the oven. Temperature control may require sophisticated exhaust and outside air blending, but safety is enhanced by a low oxygen atmosphere in the oven. The oxygen needs for fuel combustion prevent use of a totally closed system and result in more exhaust gas than can be used in the oven. Thus, the total heat recovery efficiency is low. However, exhaust-gas recirculation can be used with heat recovery for other purposes to obtain a high overall recovery efficiency.

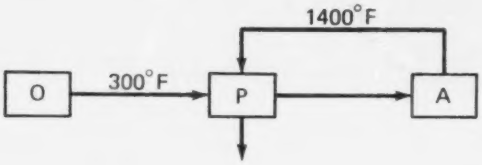


Source: *Afterburner System Study,* Shell Development Company, 1972.

Figure 15. Process Heat Recoverable from Afterburner

The following calculation shows the effect of primary heat recovery on afterburner fuel requirements in a sample case:

Example 6—Calculate the fuel savings expected by the application of a heat exchanger of 50% effectiveness, as shown in the schematic:



O: Oven

A: Afterburner

P: Primary Heat Exchanger

using data described in Example 2 (oven exhaust = 3000 acfm at 300°F, containing 500 ppm toluene).

1. Heat exchange effectiveness

$$e = \frac{C_p(T_{OO} - T_{IO})}{C_p(T_{IA} - T_{IO})}$$

where: C_p = specific heat of gas, Btu/°F

T_{IO} = Oven exhaust temperature entering the heat exchanger, °F

T_{OO} = Oven exhaust temperature leaving the heat exchanger, °F

T_{IA} = Afterburner exhaust temperature entering the heat exchanger, °F

T_{OA} = Afterburner exhaust temperature leaving the heat exchanger, °F

To avoid using C_p values between unknown temperatures, the above expression can be converted in terms of enthalpies, H:

$$e = \frac{H_{OO} - H_{IO}}{H_{IA} - H_{IO}}$$

Where subscripts have the same meaning as above.

- In this example, e = 0.50

2. Oven exhaust temperature leaving the heat exchanger, T_{OO}

- Assuming all gases are air, from Table II

$$e = \frac{H_{OO} - 4.42}{26.13 - 4.42} = 0.50$$

$$H_{OO} = 15.28 \text{ Btu/scf}$$

- From Table II, for air, the corresponding temperature

  $T_{OO} \approx 868°F$ (by linear interpolation)

3. Heat input, as in Example 1 and 2

   = (Available heat at 1400°F at 0% excess air) x G

   + (Credit for preheat of combustion air from 60°F to 868°F)

   + (Available heat from toluene)

   $= 668\ G + 15.28\ \frac{\text{Btu}}{\text{scf}} \times 10.36\ \frac{\text{scf air}}{\text{scf gas}} \times G$

   $+ 0.61 \times 4605 + 44.04 \times 15.28$

   $= 826\ G + 3482$ Btu/min

4. Heat consumption at the afterburner

   $= (2053 - 10.36 \times G - 44.04) \times (26.13 - 15.28)$

   $= 21798 - 112.4 \times G$ Btu/min

5. Heat Balance: Heat Input = Heat Consumption

   $826G + 3482 = 21798 - 112.4 \times G$

   - Solving for G,

     G = 19.5 scfm natural gas

A reduction in fuel consumption from 43.3 scfm (Example 2) to 19.5 scfm is achieved by the introduction of a heat exchanger of 50% effectiveness.

The final afterburner exhaust temperature (leaving the heat exchanger), T_{OA}, can be calculated as follows:

6. Heat Balance: Heat absorbed by oven gases in the heat exchanger - heat lost by afterburner exhaust, or

   $H_{OO} - H_{IO} = H_{IA} - H_{OA}$

   $15.28 - 4.42 = 26.13 - H_{OA}$

   $H_{OA} = 15.28$

- From Table II, for air, the corresponding temperature

  $T_{OA} \approx 868°F$

The heat contained in the incinerator exhaust at 868°F can be utilized for oven heating as well as to meet a portion of total plant steam needs. If the incinerator exhaust is used for steam production in a waste heat boiler, and if we assume the final incinerator exhaust temperature at 350°F, the heat available for steam production can be calculated as follows:

7. Heat available for steam production

   $= 2053 \text{ scfm} \times (H_{868} - H_{350})$

   $= 2053 \times (15.28 - 5.36)$ from Table II

   $= 20,366$ Btu/min

   $= 1.22 \times 10^6$ Btu/hr

This would be roughly equivalent to 1,000 lbs/hr of low pressure steam.

The choice of a heat recovery system should be made after analyzing the incinerator heat capacities and the total heat needs of the plant, using the steps below as a guide:

1. Determine the heat recoverable from the incinerator exhaust. This heat can be used for preheating the oven or for generating steam, heating water, or comfort heating.
2. Determine the preheat that can be applied to the oven exhaust, that is, the highest amount compatible with the safe maximum oven exhaust temperature.
3. Determine the heat that can be recycled to the oven as incinerator exhaust by using assumed exhaust to outside-air ratios and the known oven temperature requirement. In considering this as an option, the effect of incinerator exhaust on product quality must also be evaluated.
4. Determine the purposes for which heat recovered from the incinerator exhaust could immediately be used. During periods of incinerator operation when there is no hot water or steam demand in the plant, the value of heat recovery is limited. Heat recovery for comfort heating can be used only in the winter months.
5. Determine the heat load from steam, hot water, and comfort heating, based on past history of fuel burned for these purposes.

If the total heat demand from steps 2, 3, and 5 is comparable to the amount of heat recoverable, then the plant should consider heat recovery units with high effectiveness ratios (Table V). If the heat demand is small compared to the recoverable heat, heat exchangers with lower effectiveness can be used, thereby reducing capital costs.

CHAPTER III

COST OF COMBUSTION AND HEAT RECOVERY SYSTEMS

The combustion of dilute organic fumes in air streams is one of the most expensive forms of air pollution control. In smaller units, installed costs may range up to $25 per cfm capacity. Operating costs are also high because of the fuel consumed in heating air streams to high temperatures. Heat recovery will reduce fuel consumption but entails higher capital investment. Selecting a combustion and heat recovery system for a specific use requires careful consideration of capital and operating-cost tradeoffs to insure a minimum overall cost.

Installation costs for thermal incinerators range from 75 to 200 percent of the cost of the basic equipment, averaging about the same as equipment costs. Installation costs will normally consist of installation labor and materials, plus auxiliary equipment that consists of:

- Ducting;
- Blower motor controls and instrumentation;
- Insulation;
- Blower motor housing for noise control;
- Instrumentation, including air pressure regulator, temperature monitoring and recording, flame safety controls, and fuel rate monitoring; and
- Foundations and structural steel.

The installed costs of thermal and catalytic incinerators, with and without heat exchangers, are shown in Figure 16. Estimates were based on roof-top location with allowance for structural steel and assuming custom-designed units. The cost, therefore, may be considered as in the upper limits in the less-than-10,000 cfm range. Pre-engineered units with a few thousand cfm capacity may be installed at a total cost of approximately two-thirds that of a custom-designed and fabricated unit.

Costs of operation will depend on the number of shifts, the temperature of the contaminated air stream, and the incineration temperature. Variable cost factors are fuel and electricity consumed and labor for operation. Maintenance, taxes, insurance, and overhead charges on space are commonly taken as a fraction of capital costs. Figure 17 shows estimated operating costs for various incinerator configurations. All costs are based on an 8-hour single shift operation, inlet fume temperature of 70°F, electricity at $0.03/kWh, direct operating labor of 0.5 hr/shift, and miscellaneous

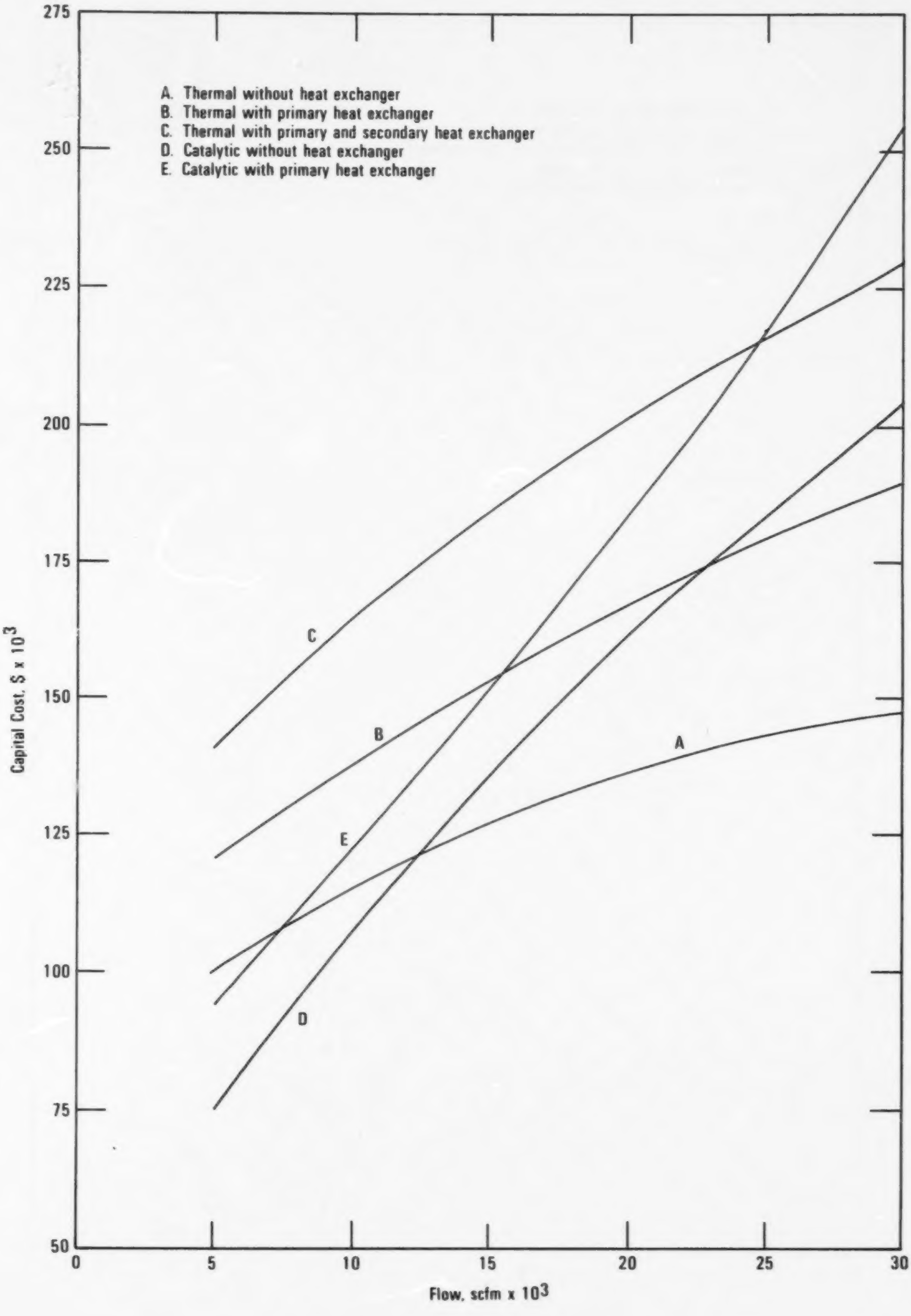


Figure 16. Capital Cost of Incineration

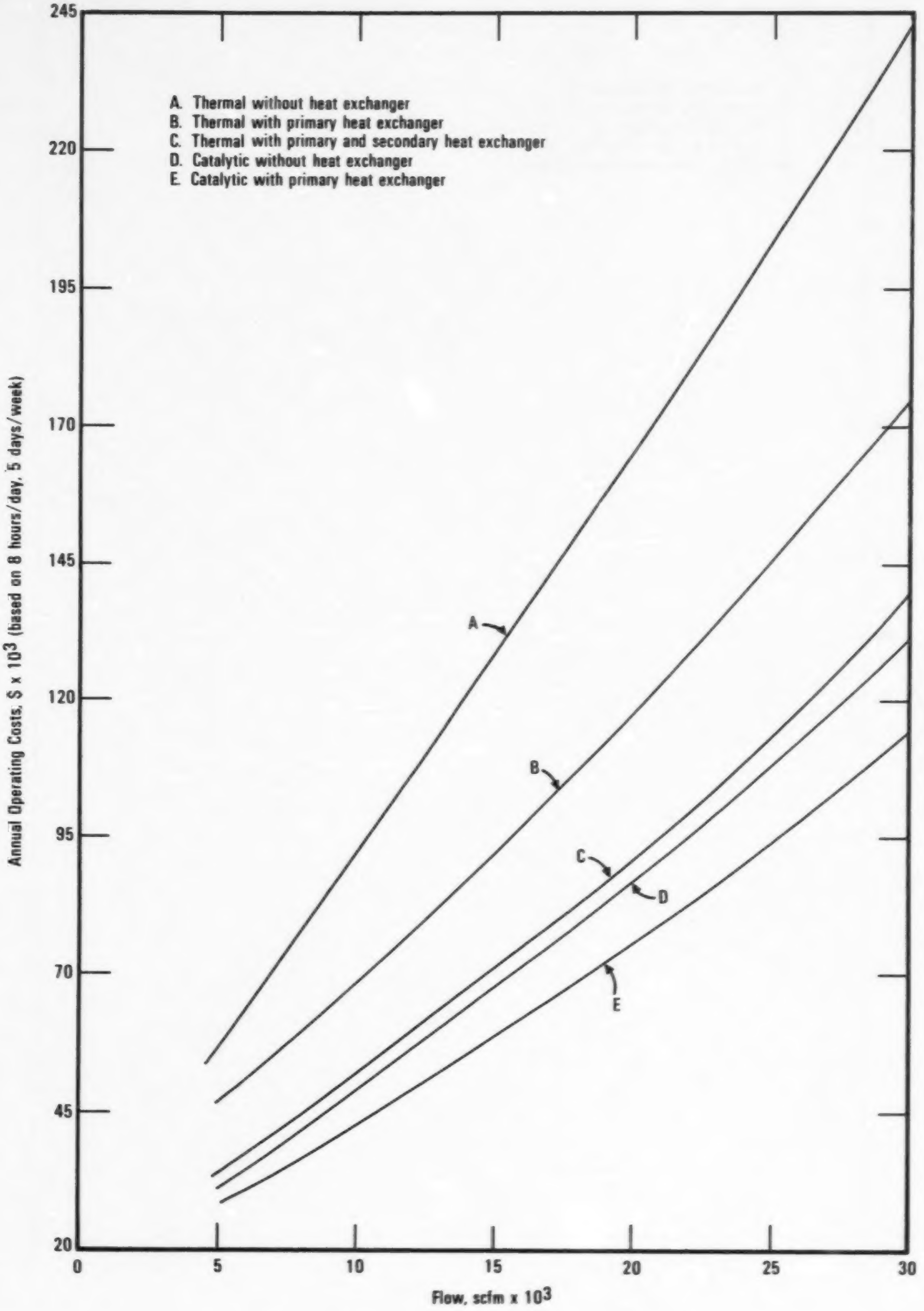


Figure 17. Annual Variable Cost of Incineration

costs of 9 percent of capital. The operating cost would increase by slightly less than factors of 2 or 3 for two- or three-shift operations.

The total annual cost of ownership may be derived from Figures 16 and 17 by combining a suitable fraction of the capital cost with the annual operating cost. At current interest levels, the annual cost of capital is commonly taken as 14-18 percent of total investment. The data in Figures 16 and 17 have been left uncombined to facilitate the approximation of total annual costs for multishift operations.

SUMMARY

The first part of this publication was concerned with reducing hydrocarbon emissions at the source through changes in coating formulas and plant equipment and processes.

In this part we have discussed, in some detail, the end-of-line treatment of emissions that must be dealt with after all other practicable control measures have been taken.

Throughout the entire volume the emphasis has been on presenting pollution control techniques as sets of options, with enough information on each method—pro and con, descriptions, diagrams, and simple calculations—for assessing its suitability for a given plant.

In both sections of this publication, plant managers, engineers, and operating personnel should find the basic information they will need to plan, in logical sequence, for reduction and treatment of hydrocarbon emissions from metal coating processes.

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